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MARCH 1914

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PRELIMINARY RESULTS OF MEASUREMENTS OF THE RIGIDITY OF THE EARTH

By A. A. MICHELSON

Installation and observations by H. G. Gale assisted by Harold Alden. Calculations by W. L. Hart under the direction of F. R. Moulton

Measurements of the temperature of the crust of the earth as found in the deepest mines show that it rises on the average about 0.02° C. for every meter below the surface; and as the rate of increase is even greater at greater depths it follows, as Lord Kelvin pointed out,[1] that the temperature in the interior must be high enough to melt the substances composing it, and for a long time it was considered that the vast bulk of the earth must be in a fluid, or at least semi-fluid, condition, a conclusion which was strongly supported by the fact of the ejection of molten lava from volcanoes.

The theoretical investigations of Lord Kelvin in 1863[2] indicated, however, that the earth must be considered a very rigid body, opposing an enormous resistance to changes of form such as tend to occur in consequence of the attractions of the sun and moon. It is evident from these investigations that the old idea (which is not entirely extinct) that we are living on a thin rock crust over an immense mass of molten lava must be abandoned.

[1] *Philosophical Transactions*, 1863. [2] *Ibid.*

The first attempt to measure the rigidity of the earth, that is, the resistance which it offers to change of shape, was made by G. H. and Horace Darwin in 1880.[1] They employed a horizontal pendulum by the use of which they hoped to measure the change in the direction of the gravitational vertical due to the attractions of the sun and moon; from which, by comparison with the values calculated on the basis of absolute rigidity, the effective rigidity could be determined. The results were so irregular and contradictory that no conclusion could be formed, and the Darwins express the belief that such experiments are not likely ever to furnish the desired results.

In the hands of Rebeur-Paschwitz this method did, however, give positive results confirming the deductions of Kelvin. Since then the method of the horizontal pendulum has been successfully employed by Ehlert, Kortazzi, Schweydar, Hecker, and Orloff, with essentially the same result, namely, that the coefficient of rigidity is found to be of the order 6×10^{11} c.g.s. (about the same as that of steel). The results deduced from Chandler's observations of the variation of the latitude give a value nearly twice as great.

But, in addition to the elastic yielding of any body ordinarily looked upon as solid there is a plastic yielding, characterized by a constant termed by Maxwell the "modulus of relaxation," and evidenced by a lag of the distortion of the earth relative to the forces producing it. Such experiments as these should be capable of determining the plasticity as well as the rigidity of the earth. To show what measure of reliability may be accorded to the observations mentioned, the following extract, Table I, is made of a discussion of these by Schweydar.[2]

Here $1-K$ represents the ratio of the observed amplitude of oscillation to that calculated on the assumption of absolute rigidity. κ represents the retardation (which should always be negative) of the phase of the observed motion relative to the phase of the disturbing forces.

[1] *B.A.A.S. Reports*, York meeting, 1880.

[2] Dr. Wilhelm Schweydar, *Untersuchungen über die Gezeiten der Festen Erde*. Potsdam, 1912; Leipzig: B. G. Teubner.

The observations are divided into two classes, the latter being considerably more reliable than the former.

TABLE I

Experimenter		K	κ
v. Rebeur		0.362	+ 7°30′
Kortazzi		.608	0
"		.414	− 2°54′
Ehlert		.448	+12° 1′
Schweydar		.338	− 8°31′
"		.158	+ 8°29′
N.–S.	Hecker	.643	−11°.9
	"	.565	− 0°.7
	"	.544	+13°.4
	Orloff	.412	+ 0°.8
E.–W.	Hecker	.259	− 7°.0
	"	.382	+ 5°.2
	"	.468	+20°.1
	Orloff	0.326	+ 3°.2

While the numbers in the second column agree in showing that the earth's rigidity is of the order of that of steel, the differences are so considerable that it is hardly likely that they can be relied upon to within 20 per cent.

If accurate, the third column would give a measure of the plastic yielding of the body of the earth to the action of the distorting forces of the sun and moon. As mentioned before, these should all be negative, whereas the great preponderance is in the direction of positive lag, which is meaningless; so that further than showing that the lag is small (and therefore the viscosity high) these results are practically valueless.

It will be conceded that there is great need for more accurate determinations, if our knowledge of the properties of the matter constituting the earth's interior is to be increased; and it was in the hope of obtaining results of a higher order of accuracy, as well as such directness and simplicity of apparatus as practically to eliminate all the difficulties and uncertainties which seem to be unavoidable in the use of the horizontal pendulum, that the experiments recorded here were undertaken.

The prime object of the investigation is the determination of the direction of the gravitational vertical, or rather of the changes

to which it is subject in consequence of the attraction of the sun and moon and as modified by the resulting distortion of the body of the earth. But this may be furnished with any desired degree of accuracy by the changes in the position of the level of a liquid surface which is necessarily normal to the resultant of all the forces acting. If from these we can eliminate all but the gravitational forces the problem is solved.

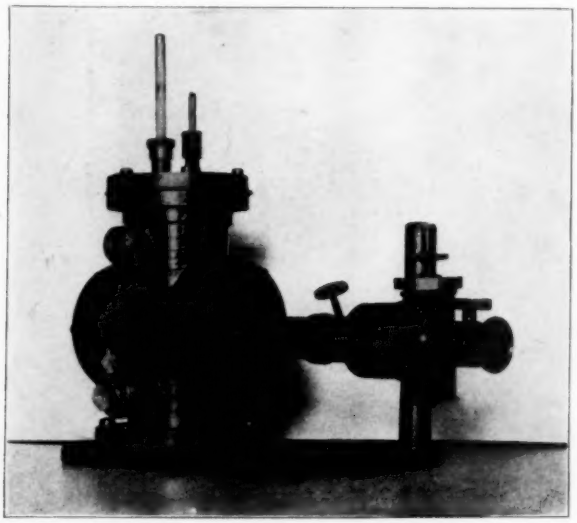


FIG. 1.—Microscope and gauge

A very sensitive method of measuring the changes in level is furnished by the interferometer; and a method of carrying this into practice was devised and the apparatus constructed[1] in 1910.

But before attempting to utilize so delicate an appliance it was deemed advisable to make these preliminary experiments with the microscope. Accordingly a 6-inch pipe, 500 feet long, was half filled with water,[2] the level of which could be read off through the glass sides of the end vessels, as shown in Fig. 1.

[1] An interference apparatus for this purpose was independently devised by Professor A. G. Webster.

[2] The vessels at the ends were at first connected by a pipe filled with water, but with this arrangement temperature changes produced enormous disturbances in the level.

This pipe was laid in a trench six feet deep, terminating in two pits, eight feet square and ten feet deep, walled with concrete, in a soil of sandy clay on the grounds of the Yerkes Observatory at Williams Bay, Wisconsin. The direction (E.–W.) of the pipe was laid out by measuring from the meridian line and is probably correct to within one foot in five hundred. The pipe was then carefully leveled, and after verifying the continuity of the water and

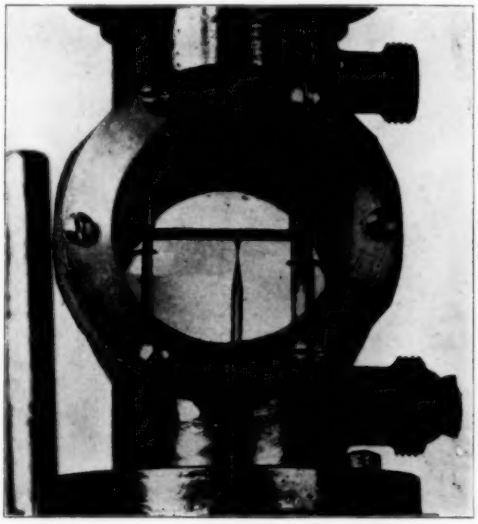


FIG. 2.—Point and totally reflected image

of the air space above it, the pipe was closed so that it was effectively air-tight, and the trench was filled with clay.

The distance between the total reflection image of a pointer, Fig. 2, and the direct image was read by micrometer microscopes of about 2-inch focus. These were calibrated at first rather roughly by measuring the diameter of a wire immersed in the water at the focus; and subsequently with much greater accuracy by measuring the known distance between two lines, ruled on glass and placed in the focus, under water.

A preliminary series of observations was begun August 5 and continued until September 2 with such encouraging results that it

was decided to supplement the work by observing on a N.–S. line which was accordingly laid out in the same manner as the E.–W. line.

The final calibration of the microscopes gave the following results:

West	17.52 turns	= 1 mm
East	17.60 "	= 1 mm
North	17.00 "	= 1 mm
South	17.60 "	= 1 mm

The mean for the E.–W. line is 17.56, and for the N.–S. line, 17.30. Accordingly the factor by which the calculated difference in level in mm should be multiplied to reduce to micrometer divisions is

For the E.–W. line, 285
For the N.–S. line, 289

The factor actually used in the computation was 293, and accordingly these should be diminished by 2.8 per cent for the E.–W. line, and by 1.4 per cent for the N.–S. line.

A continuous series of observations was conducted on both lines, beginning September 27 and ending November 29. The observations were made by setting the cross-hair of the micrometer on the pointer and taking a number of readings, the mean of which gave the fiducial reading to be subtracted from the readings of the reflected image. This difference was subtracted from a similar difference taken at the other end of the pipe, and the final differences from hour to hour (plus a constant) gave the observed curves. These readings were taken every hour from 6 A.M. until midnight, and every two hours from midnight until 6 A.M. The order of the observations was usually south end, north end, east end, west end. The time between readings at south end and north end, or between east end and west end, was about four minutes, and the mean between the two was taken to represent the time of observation. The mean time of the two observations gives the same result as though the observations had been simultaneous.

Occasionally the reflected image would be obscured by floating particles, and in clearing these away the value of the constant would be altered. The new constant was accordingly chosen so that the succeeding observations continued with the smallest discontinuity in the curve.

It was found that there was a gradual downward trend in the E.–W. curve during August, but little or none in the October-November series. The N.–S. line, however, on which readings were started the day after the pipe was covered, shows a considerable gradual drop. This was undoubtedly caused by uneven settling at the ends of the pipes. This was too slow to affect the result for the semi-diurnal period, but made doubtful the results for the fortnightly period.

The observations and their graphs are given in Tables III and IV and in Figs. 3 and 4.

In Figs. 5 to 12 these graphs are reproduced on a larger scale, together with those of the calculated values of the readings, multiplied by the factor 0.7 for the E.–W. line and 0.5 for the N.–S. line. The zero line of the observed readings is corrected to coincide with the calculated curve.

These curves were divided into periods corresponding to the semi-diurnal lunar tide, 12.42 hours, and the values at corresponding intervals of two hours tabulated and divided into groups of ten periods each.

The results of the comparison of the observed and calculated curves is given in Table II, in which the first column gives the ratio of the observed amplitudes to the calculated, on the assumption of an absolutely rigid earth, and the second the retardation of phase in hours.

TABLE II

Ratio of Amplitudes		Retardation in Phase	
E.–W.	N.–S.	E.–W.	N.–S.
0.69	0.50	-0^h05	-0^h06
.79	.54	+ .30	+ .30
.65	.53	− .14	− .08
.71	.50	− .01	− .03
.82	.53	− .08	+ .12
.64	.52	− .14	− .20
.66	.50	− .08	.00
.70	.50	− .03	.00
.70	.50	− .12	− .06
.74	.50	− .16	− .02
.70	.48	− .12	+ .08
0.71	0.52	−0.08	+0.04
Mean = 0.709 × 1.028	0.510 × 1.014	−0.059	+0.0075

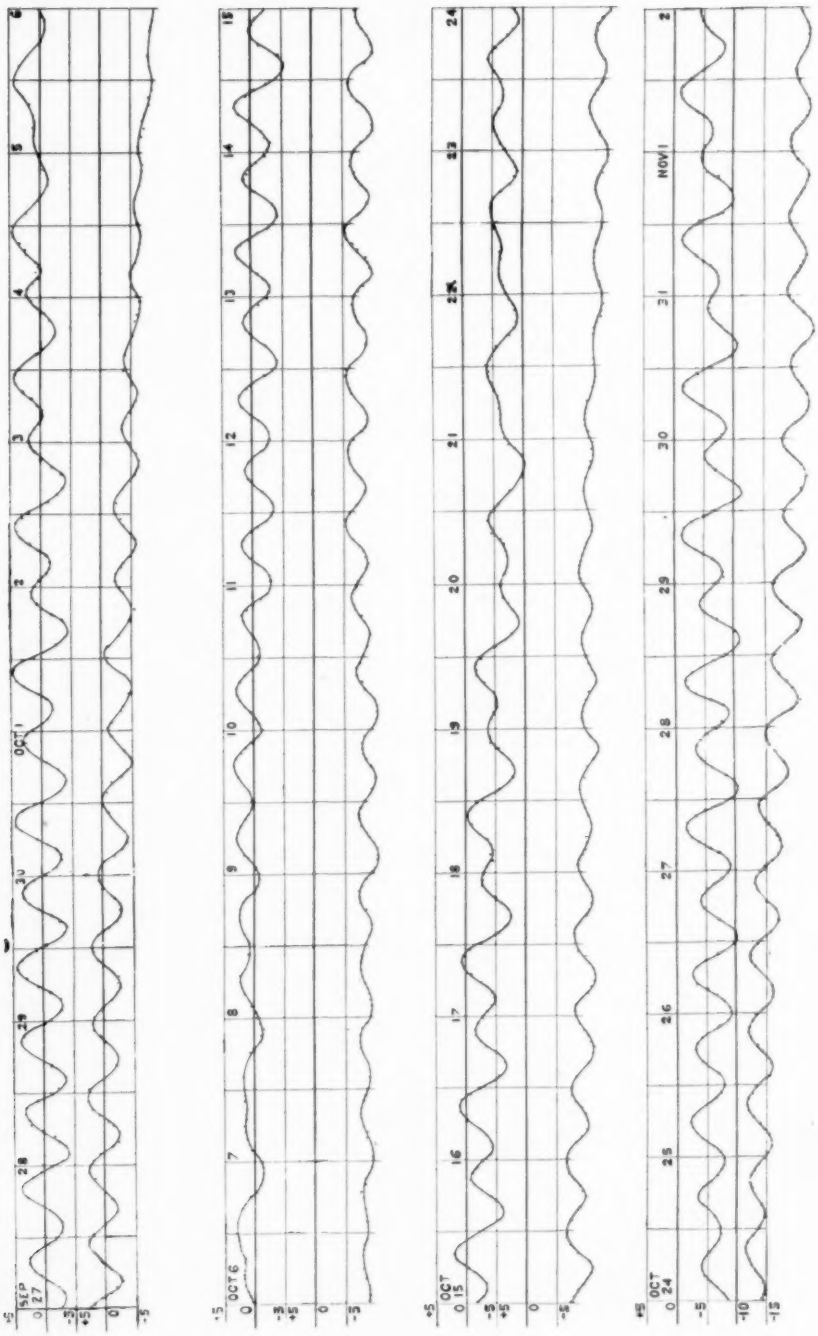


FIG. 3.—Upper curves, 10(E.−W.+C); lower curves, 10(S.−N.+C)

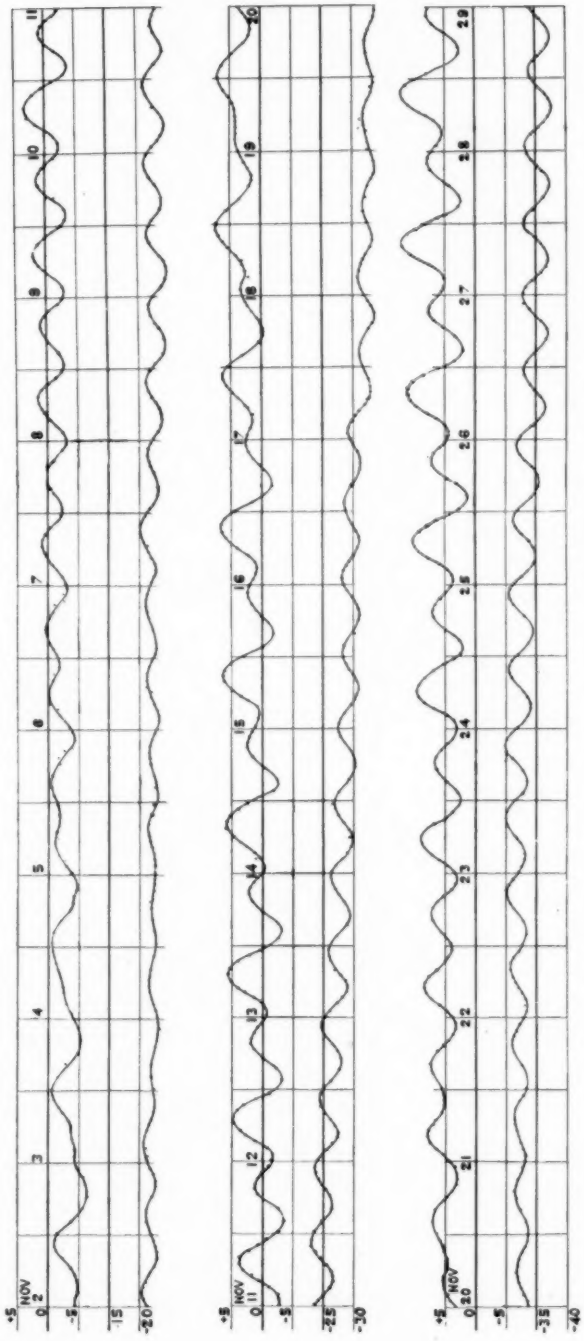


FIG. 4.—Upper curves, 10(E.−W.+C); lower curves, 10(S.−N.+C)

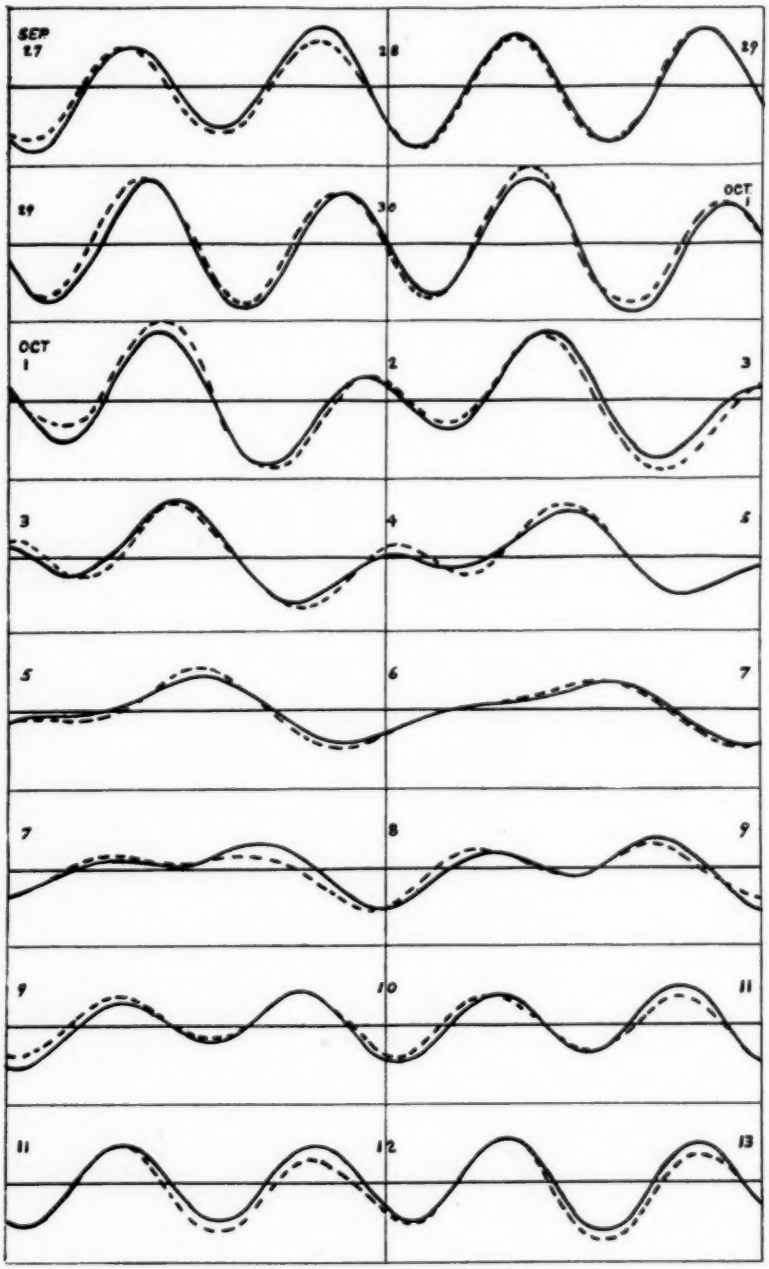


FIG. 5.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

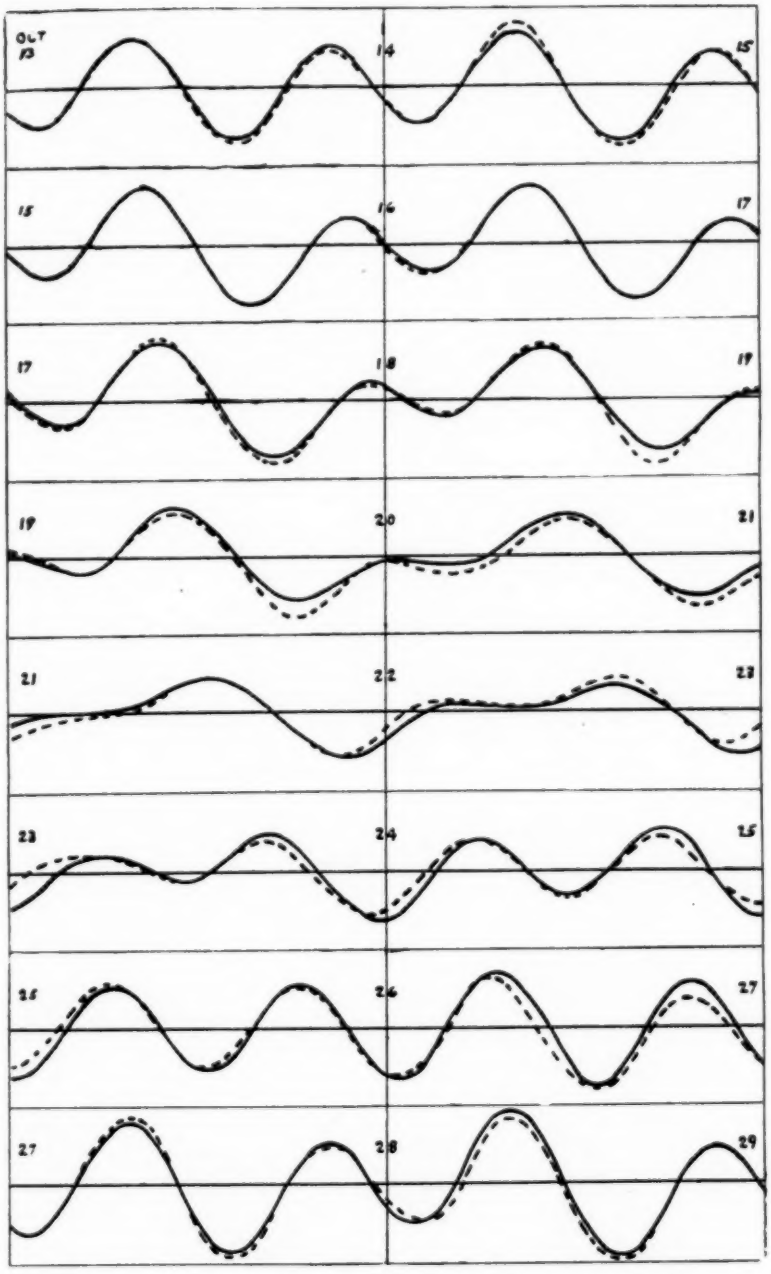


FIG. 6.—E.–W. Dotted curve, observed values; full curve, 0.7 of calculated

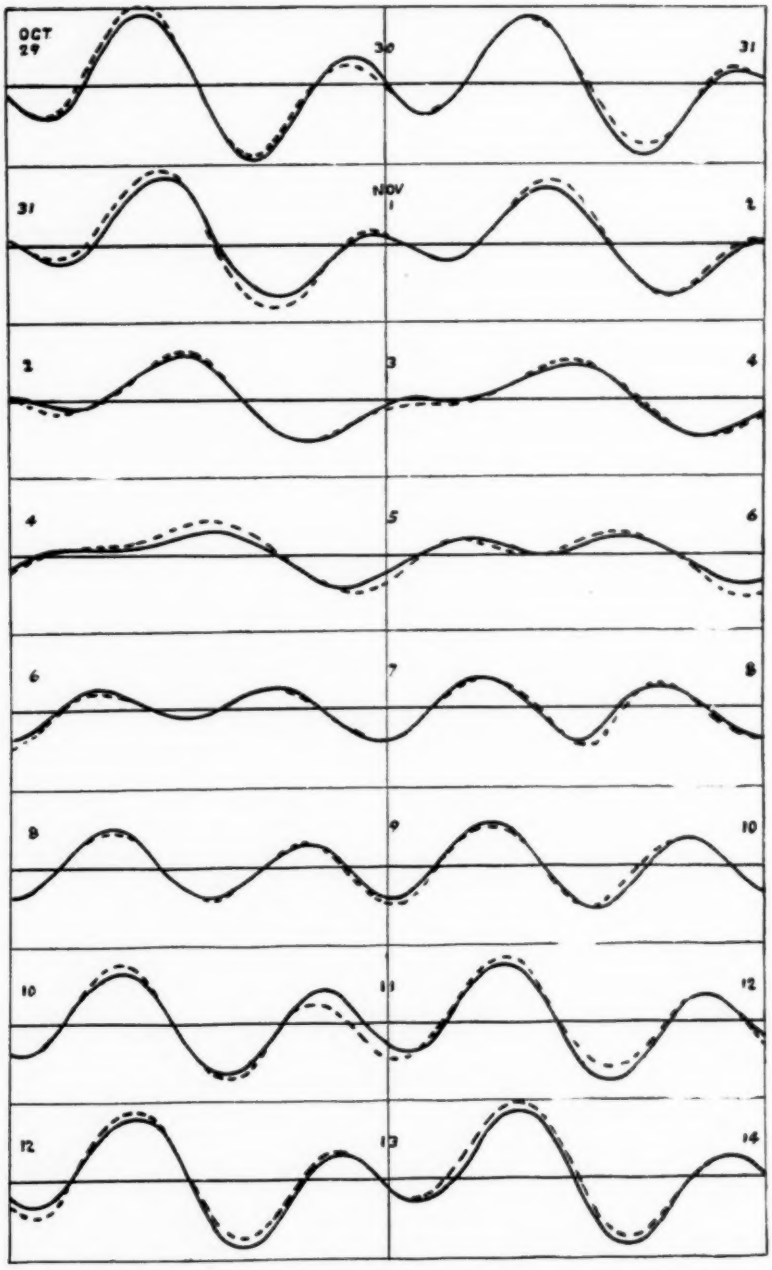


FIG. 7.—E.-W. Dotted curve, observed values; full curve, 0.7 of calculated

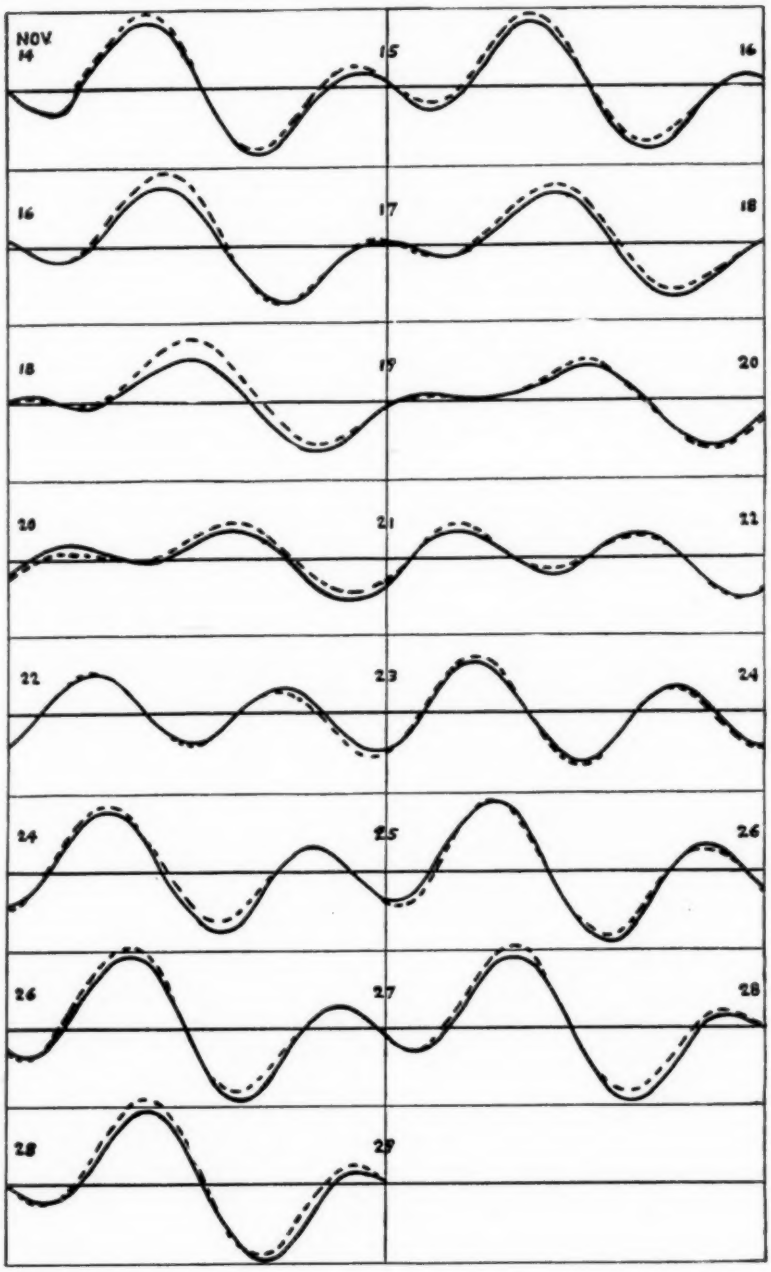


FIG. 8.—E.–W. Dotted curve, observed values; full curve, 0.7 of calculated

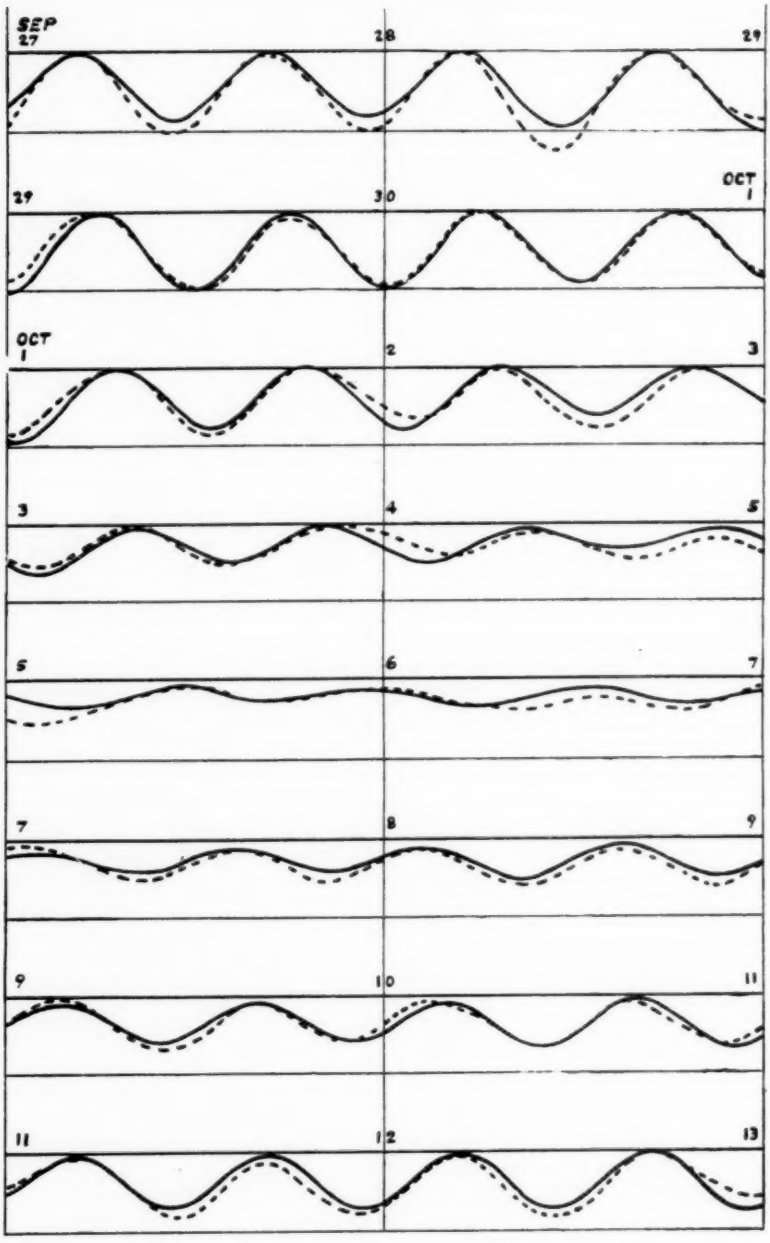


FIG. 9.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

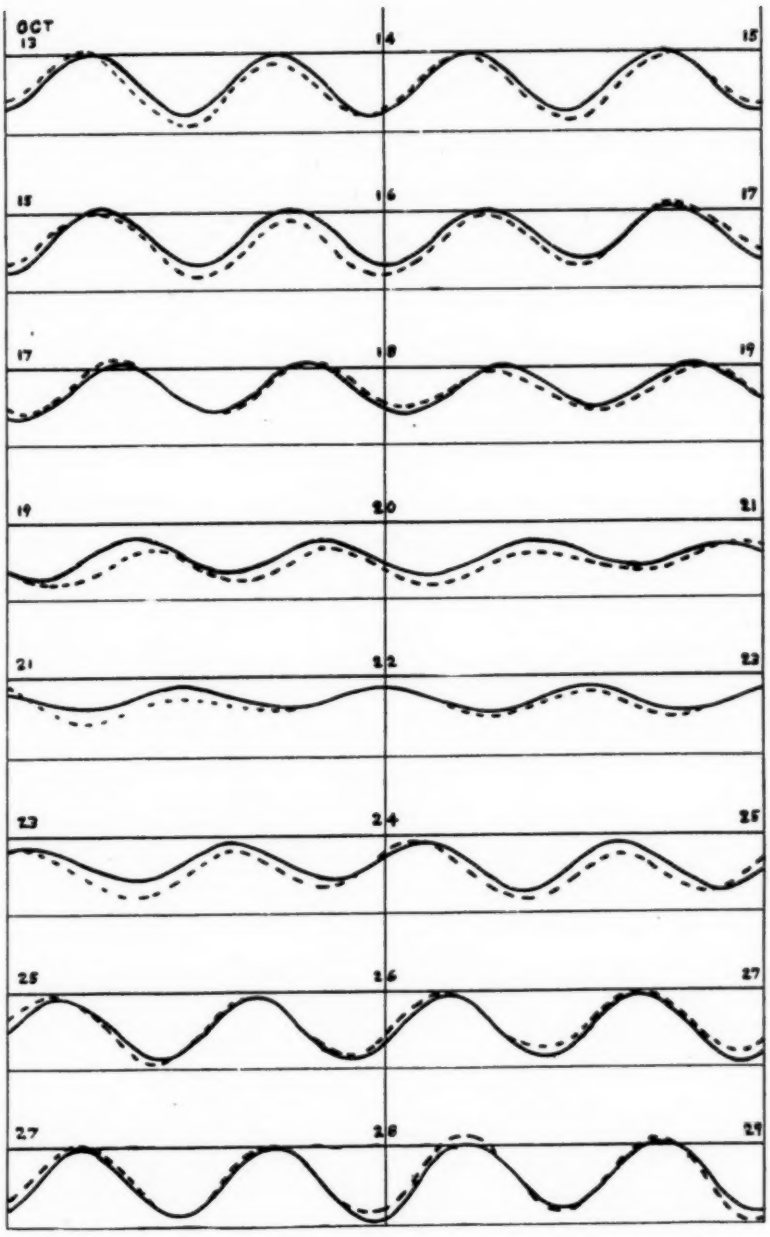


FIG. 10.—N.–S. Dotted curve, observed values; full curve, 0.5 of calculated

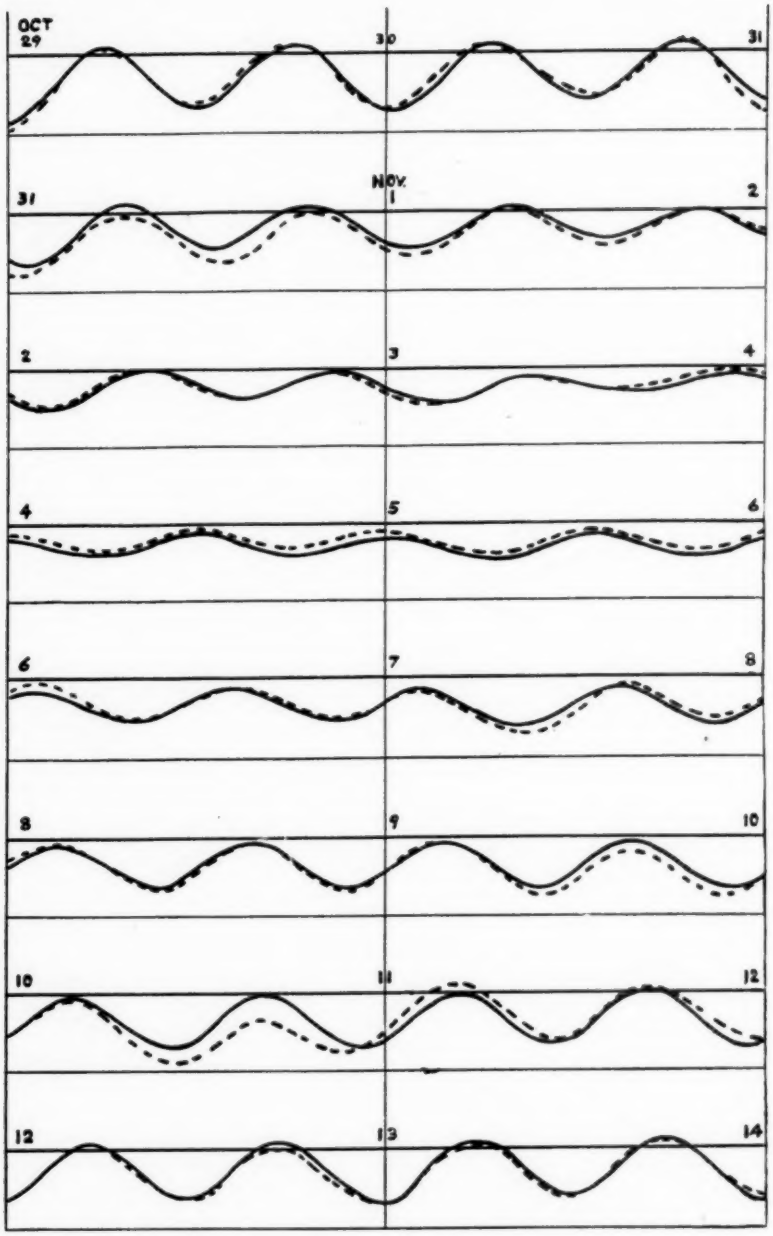


FIG. 11.—N.–S. Dotted curve, observed values; full curve, 0.5 of calculated

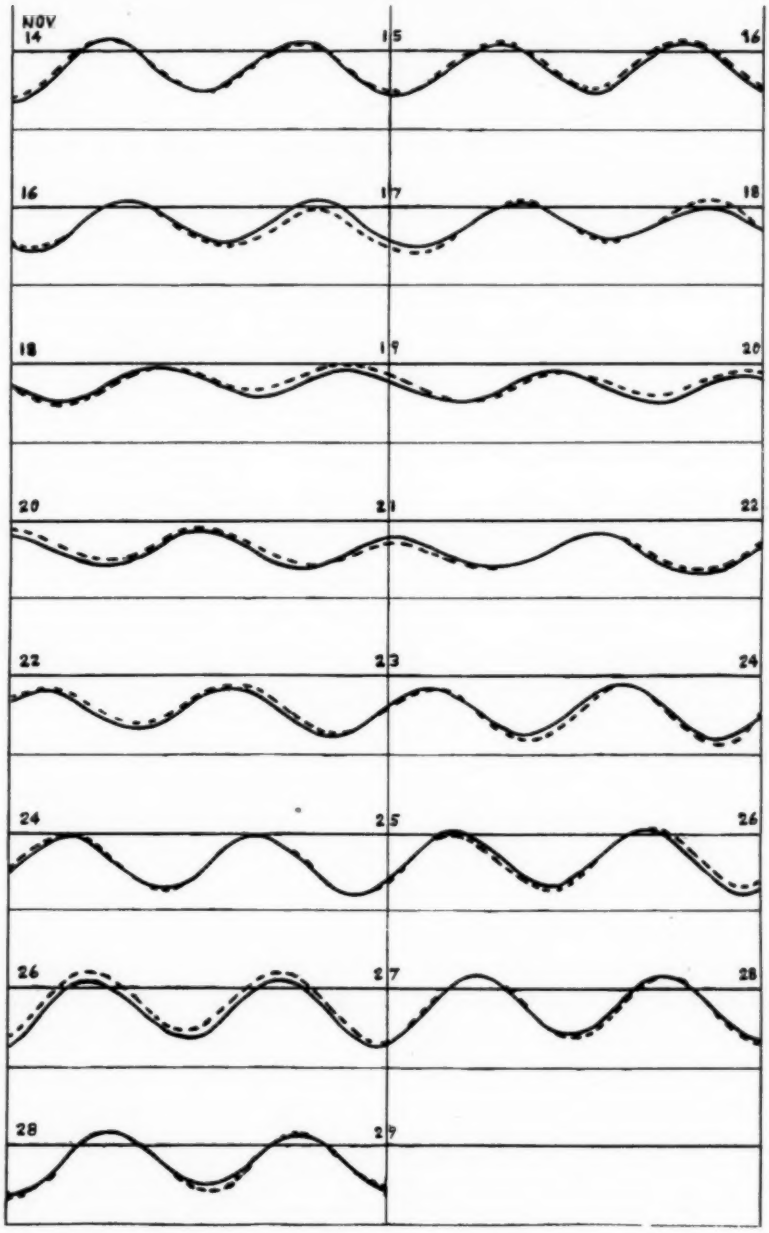


FIG. 12.—N.-S. Dotted curve, observed values; full curve, 0.5 of calculated

The resulting mean of all observations, for this method of grouping, is that the observed amplitude of the oscillation for the E.–W. line is 0.709 of that calculated on the assumption of absolute rigidity; while for the N.–S. line it is 0.510. The acceleration of phase of the observed oscillations relative to the calculated is $+0^h.059$ for the E.–W. line and $-0^h.007$ for the N.–S. line. The graphs of the final means of all the observations and the calculated values are reproduced in Figs. 13 and 14.

The curves correspond very closely with the following formulae:

$$\text{E.–W.} \quad y = -a \sin \frac{2\pi}{T}(t-\tau)+b$$

$$\text{N.–S.} \quad y = -a \cos \frac{2\pi}{T}(t-\tau)+b$$

with the following values for the constants:

E.–W.

Calculated × 0.7	Observed
$a = 20.56$	$a = 20.30$
$\tau = 0.99$	$\tau = 0.88$
$b = 0.33$	$b = 0.30$

N.–S.

Calculated × 0.5	Observed
$a = 13.18$	$a = 13.60$
$\tau = 0.99$	$\tau = 0.97$
$b = 0.16$	$b = 0.13$

Accordingly the ratio of the observed to the calculated amplitude for E.–W. is 0.691, and for N.–S. is 0.516, while the phase accelerations are $0^h.11$ and $0^h.02$ respectively.

These last results are slightly different from the preceding. The preference is for the latter as regards amplitude ratios, but these give relatively too much weight to the large oscillations in deducing the phase-difference, and for these the former results are preferred.

Multiplying the second set of values obtained for the amplitude ratios by the factors given above, 1.028 for E.–W. and 1.014 for N.–S., the final results are:

Amplitude Ratio	Phase Acceleration
E.–W. 0.710	**E.–W. ..... +0.059 hour**
N.–S. 0.523	**N.–S. ..... −0.007 hour**

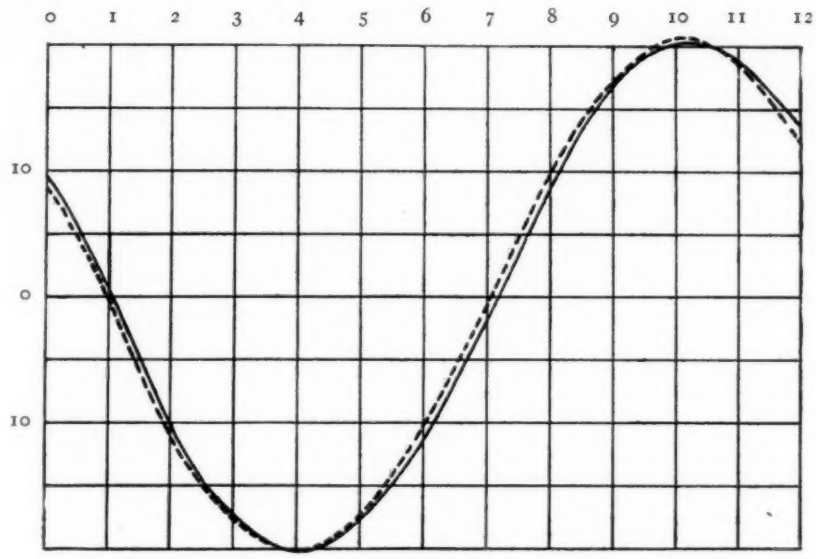


FIG. 13.—Mean of all observations, semi-diurnal Lunar tide. Dotted curve, observed values; full curve, 0.7 of calculated.

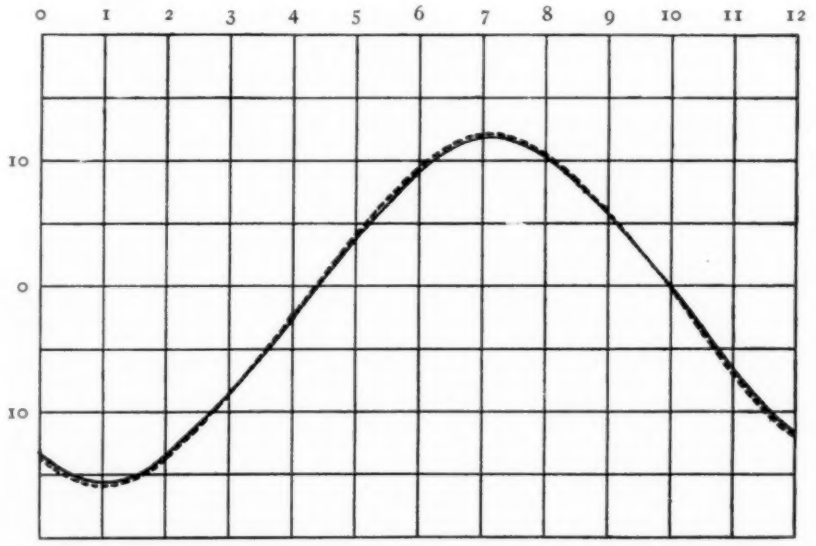


FIG. 14.—Mean of all observations, semi-diurnal Lunar tide. Dotted curve, observed values; full curve, 0.5 of calculated.

It is estimated that the errors in the amplitude ratios are under 1 per cent. The phase acceleration is probably correct to within 0^h03, but is so small as to leave some doubt as to whether or not it is real.

The disagreement between the E.–W. and N.–S. directions has been interpreted by Hecker, who found a similar difference, as

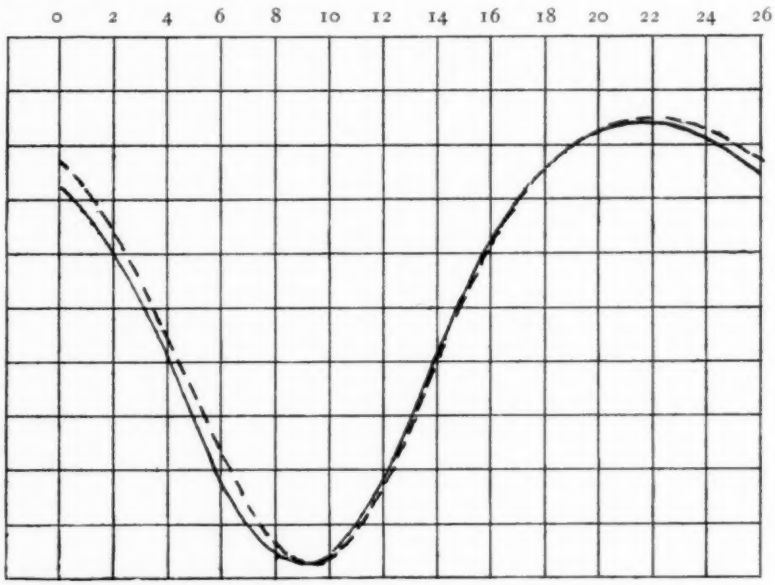


FIG. 15.—E.–W. Mean of observations of diurnal Lunar tide. Dotted curve, observed values; full curve, 0.7 of calculated.

indicating an actual difference in the earth's rigidity in the E.–W. and N.–S. directions.

Schweydar agrees with A. E. H. Love in attributing the difference to the effect of ocean tides, and shows on the assumption of an ocean covering the earth uniformly to a depth of 5000 meters that the tides have the effect of increasing the elastic earth tides, so that the ratio of the observed amplitudes to the theoretical is diminished by something like 40 per cent.

The mean values of the ratio adopted by Schweydar are 0.61 for E.–W. and 0.46 for N.–S., which should therefore be increased

to 0.85 and 0.64 respectively. A similar correction applied to the results of these experiments would give, instead of 0.71 and 0.52, the values 0.99 and 0.73. The E.–W. value would mean that the earth's rigidity is practically infinite, and it is undoubtedly too high.

The ocean is, however, anything but uniform in depth, and this and the irregularities in coast lines, make an accurate calculation of the disturbing effect of the ocean tides almost impossible. Accordingly Schweydar, considering that the results furnished by

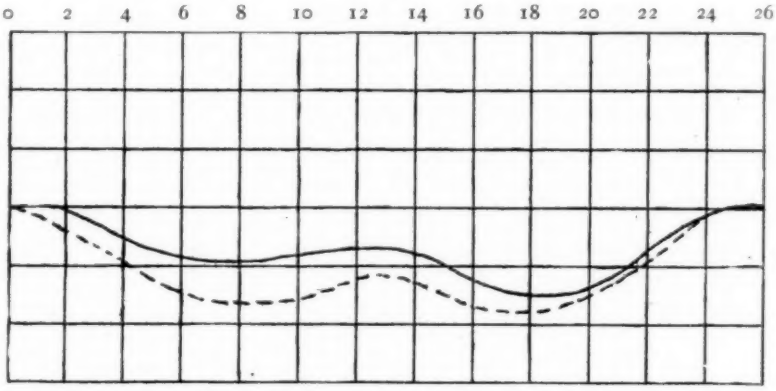


FIG. 16.—N.–S. Mean of observations of diurnal Lunar tide. Dotted curve, observed values; full curve, 0.5 of calculated.

the consideration of the semi-diurnal tides is not reliable, investigated the problem of the diurnal period, especially that corresponding to the "declination tide" whose period is $25^h.812$. The dynamical theory shows that for an ocean entirely covering the earth, such tides should vanish; a result which is approximately true, at least for the Atlantic.

This analysis applied to Hecker's observations gives 0.85, as the value of the ratio, which, it will be noticed, agrees with the value for the semi-diurnal period when corrected for the calculated perturbation of the ocean tides.

The result of grouping the present observations into six groups of two periods each (of $25^h.81$) is reproduced in the graphs of Figs. 15 and 16.

These were analyzed by means of the harmonic analyzer, and

gave the following results, in which R is the ratio of the observed amplitude to the calculated, and ϕ the phase acceleration:

	R	ϕ
E.–W.....	0.72	−0.4 hour.
N.–S.....	0.66	+1.0 "

It appears therefore that the diurnal period gives for the amplitude ratios numbers which are decidedly in better agreement than those furnished by the semi-diurnal period.

It is to be noted that while the agreement between the E.–W. and the N.–S. results is considerably improved, the value of R for the E.–W. direction has not been altered, whereas according to Schweydar's investigation it should have been much larger (0.90 or more). It may be, however, that first, in consequence of the smaller number of periods entering the calculation, and secondly, on account of the smaller value of the resulting amplitude (41 : 100), these numbers have a considerably larger probable error than that of the semi-diurnal period.

Possibly a closer analysis of the actual ocean tides would show that the effect is small for the E.–W. direction, while in the N.–S. direction it may be considerable.

Regarding the acceleration of phase, it may be noted that the difference between the E.–W. and the N.–S. direction is much greater for the diurnal period than for the semi-diurnal, whereas, if the results of the latter were seriously affected by the ocean tides, the reverse should hold. The mean of the semi-diurnal accelerations is $0^h.03$, a quantity so small that it is within the probable error. Taking this value together with 0.70 as the ratio of the observed to the calculated amplitudes, the corresponding values of the earth's rigidity n and viscosity ϵ are:

$$n = 8.6 \times 10^{11} \text{ c.g.s.}$$
$$\epsilon = 10.9 \times 10^{16} \text{ c.g.s.}$$

This calculation is based on the assumption of uniform rigidity throughout the body of the earth, a condition which is certainly not fulfilled; and that as the time increases in arithmetical progression the stresses diminish in geometrical progression. It is clear, however, that the earth's rigidity is greater than that of steel. If the

ocean tides have the effect of diminishing the ratio R by from $\frac{1}{2}$ to $\frac{1}{3}$, as admitted by Schweydar, the rigidity is enormously greater.

The viscosity is also very great and probably of the same order of magnitude as that of steel.

The main object of this investigation was to demonstrate the feasibility of the method and to determine the order of magnitude of the earth's rigidity and viscosity. Evidently the method is capable of giving results of a high order of accuracy by recording a much longer series of observations. Such a series, in which the microscope will be replaced by the interferometer and in which the record is to be made automatic, is now in preparation. It is expected that the results will furnish a record of the earth tides which will be correct to within a tenth of 1 per cent.

Whether it may thereby be possible to obtain a more accurate value of the coefficients of rigidity and of viscosity will depend on the advance which may be made in the theory of the ocean tides and of their perturbing action. Doubtless it would be of importance to repeat the experiments at widely different stations, some in the southern hemisphere, some on islands in mid-ocean, and some on the continent as far as possible from the coast.

It may also be possible by a comparison of the moon and the sun tides to obtain an independent and perhaps more accurate value of the moon's mass.[1]

The conclusions from these and similar experiments and observations, including precession and variation of latitude, all agree substantially in refuting the old notion that the internal temperature, sufficiently high to melt most of the materials constituting the earth's crust, necessarily involves a fluid or semi-fluid earth supporting a relatively thin solid crust.

From the definitely ascertained result that the coefficient of rigidity and the coefficient of viscosity are both very large (of the order of, and perhaps exceeding, those of solid steel, whereas under normal pressure all substances at this temperature would be fluid), it follows that pressure increases the rigidity and the viscosity, at least of the substances which form the body of the earth.

[1] It would probably be necessary to make use of a tunnel sufficiently deep to eliminate the thermal effect, which even in the semi-diurnal period would be appreciable.

It would be interesting to confirm this important conclusion, even qualitatively, by experiments on the effect of such relatively small pressures as we are able to obtain in the laboratory.

Such experiments are now in progress; and while the highest pressures obtainable are a thousand times smaller than the pressure in the interior of the earth, it may be stated that there are distinct indications of an increase in the coefficient of rigidity, and a marked increase in the coefficient of viscosity of the few materials thus far investigated.

I would take this opportunity of expressing my appreciation of the interest taken in this work by Professor T. C. Chamberlin, at whose instigation the investigation was undertaken, and of tendering thanks to him and to President H. P. Judson for their efforts in securing the necessary funds. I would also gratefully acknowledge the friendly co-operation of Professor Frost and the members of the staff of the Yerkes Observatory.

TABLE III 10(E.−W.+C.)

A.M. September 27	A.M. September 30	P.M. October 2	A.M. October 5	A.M. October 8
C=+1.30	12:12 − 0.6	4:10 − 1.3	11:32 ± 0.0	6:29 + 0.7
	2:12 − 3.6	5:08 − 1.0	1:02 + 0.9	7:03 + 0.2
8:16 + 1.6	3:12 − 4.1	6:08 + 0.7	2:46 + 1.0	8:08 − 0.9
9:11 + 0.7	4:14 − 2.8	7:14 + 1.8	4:04 + 1.1	9:06 − 1.0
10:12 − 0.8	5:12 − 1.3	8:11 + 3.4	5:17 + 0.9	10:22 − 1.5
11:16 − 2.4	6:18 + 0.6	9:09 + 3.9	6:07 + 1.2	11:14 − 0.8
11:56 − 2.7	7:18 + 2.3	10:31 + 4.2	8:08 + 1.9	12:14 − 0.5
1:10 − 3.3	8:20 + 3.1	11:30 + 3.0	9:22 + 2.9	1:08 − 0.3
2:10 − 3.2	9:56 + 3.0	12:30 + 2.0	10:27 + 3.9	2:08 + 0.4
3:15 − 2.1	11.02 + 1.5	2:02 − 1.2	12:06 + 4.4	3:10 + 0.8
4:06 − 0.1	12:04 − 0.3	3:18 − 2.6	2:24 + 3.6	4:06 + 1.7
5:14 + 0.6	1:12 − 2.3	4:14 − 3.6	4:11 + 2.1	5:09 + 2.1
5:48 + 1.8	2:20 − 3.1	6:40 − 3.3	6:31 ± 0.0	5:53 + 2.2
7:08 + 2.5	3:20 − 3.0	7:58 − 1.8	8:34 − 1.1	7:05 + 2.7
8:16 + 2.5	4:14 − 2.2	9:10 ± 0.0	9:18 − 0.8	8:06 + 1.7
9:19 + 1.2	5:10 − 0.8	10:20 + 1.0	C= +3.00	9:22 + 1.1
10:26 − 0.4	5:52 + 0.8	11:10 + 1.5		10:35 + 1.1
11:12 − 1.8	7:11 + 3.4	12:06 + 2.2	10:18 − 0.7	12:23 + 0.8
12:14 − 2.8	7:53 + 4.2	1:18 + 1.8	11:22 − 0.1	1:54 + 1.7
2.04 − 2.9	10:32 + 3.3	2:14 + 1.1	12:15 + 0.3	4:19 + 2.4
4:04 − 0.8	1:46 − 3.0	3:14 + 0.2	1:23 + 0.9	6:10 + 2.5
6:09 + 2.8	3:31 − 3.9	4:15 − 0.2	2:16 + 1.2	7:10 + 1.9
9:30 + 1.8	4:21 − 3.7	5:06 − 0.2	3:18 + 1.6	8:02 + 1.2
10:26 + 0.4	5:28 − 2.6	5:45 + 0.2	4:24 + 1.7	9:12 + 0.1
11:15 − 1.1	6:30 − 0.8	7:09 + 1.7	5:02 + 1.7	10:06 − 0.5
12:22 − 3.0	8:39 + 2.4	8:22 + 3.1	5:54 + 1.9	11:12 − 0.9
1:17 − 4.1	9:48 + 2.7	9:48 + 4.2	7:04 + 1.5	12:08 − 0.7
2:40 − 3.7	11:12 + 2.8	11:14 + 4.4	8:24 + 2.1	1:08 − 0.3
3:33 − 2.4	11:59 + 1.5	12:06 + 3.5	9:18 + 2.5	2:15 + 0.7
4:12 − 1.8	1:38 − 0.9	2:38 + 0.8	10:14 + 2.5	3:06 + 0.7
5:04 + 0.1	3:20 − 1.8	5:42 − 2.1	11:10 + 2.7	4:16 + 2.0
6:12 + 2.1	4:10 − 1.7	8:02 − 1.6	12:05 + 3.1	5:14 + 2.8
7:08 + 2.3	5:13 − 0.6	9:09 − 0.6	2:07 + 3.1	5:54 + 2.9
8:06 + 3.0	5:51 + 0.5	10:10 + 0.8	4:18 + 2.1	7:00 + 2.8
9:08 + 3.0	7:17 + 3.1	11:19 + 1.5	6:19 + 0.6	8:10 + 2.4
10:20 + 1.0	8:05 + 4.3	12:16 + 2.5	7:10 − 0.2	9:22 + 1.5
11:28 − 1.4	9:22 + 5.0	1:22 + 2.2	8:22 − 0.8	10:06 + 1.0
12:20 − 2.5	C= −1.32	2:08 + 1.2	9:12 − 1.2	11:12 + 0.3
2:11 − 3.6		3:23 + 0.4	10:16 − 1.0	12:22 + 0.3
4:18 − 1.2	10:12 + 4.7	4:10 + 0.8?	11:14 − 1.1	2:10 + 0.8
8:20 + 3.8	11:14 + 3.2	5:01 + 0.3	12:01 − 1.1	4:25 + 2.5
9:14 + 3.3	12:10 + 1.2	5:58 + 0.7	1:04 − 0.6	6:16 + 3.3
10:08 + 3.1	2:10 − 2.4	7:16 + 2.2	2:08 + 0.3	7:20 + 3.1
11:18 − 0.2	4:16 − 4.6	8:02 + 2.5	3:06 + 0.9	8:13 + 2.0
11:58 − 1.2	6:28 − 3.4	9:06 + 3.5	4:10 + 1.2	9:08 + 1.3
1:19 − 3.0	7:15 − 1.8	10:16 + 4.6	5:08 + 1.7	10:08 + 0.5
2:06 − 3.3	8:22 − 1.4	11:08 + 4.7	6:02 + 1.8	11:10 − 0.7
3:10 − 3.0	9:10 + 0.6	12:12 + 4.4	7:17 + 1.5	11:58 − 1.4
4:20 − 1.2	10:05 + 1.5	2:09 + 2.4	8:08 + 1.4	1:10 − 0.8
5:21 + 0.8	11:12 + 1.6	4:20 + 0.3	9:05 + 1.3	2:10 − 0.5
6:49 + 2.9	12:00 + 1.1	6:39 − 1.1	10:12 + 1.8	3:12 + 0.4
8:32 + 4.4	1:08 + 0.4	7:40 − 1.2	11:11 + 1.7	4:10 + 1.3
9:50 + 3.5	2:21 − 1.0	9:10 − 0.5	12:05 + 1.7	5:12 + 2.3
11:15 + 1.2	3:09 − 1.4	10:33 ± 0.0	2:16 + 1.9	5:59 + 2.8

TABLE III—*Continued*

P.M. October 10	P.M. October 13	A.M. October 16	P.M. October 18	P.M. October 21
6:53 + 2.9	1:18 − 2.9	6:00 − 4.1	6:51 − 2.4	2:12 − 6.7
8:10 + 2.2	2:24 − 2.9	7:13 − 2.4	8:30 − 0.9	3:20 − 6.4
9:18 + 1.4	3:27 − 1.9	8:02 − 1.4	9:52 − 0.2	4:10 − 6.3
10:14 + 0.3	4:14 − 1.0	9:06 − 0.7	11:00 − 0.7	5:04 − 6.4
11:14 − 0.8	5:11 + 0.2	10:10 − 1.0	12:00 − 1.7	6:00 − 6.0
12:34 − 1.1	5:59 + 1.3	11:06 − 1.8	2:05 − 5.3	7:00 − 5.9
1:50 − 1.1	6:52 + 2.2	12:06 − 2.5	4:06 − 7.9	8:02 − 5.8
4:11 + 0.2	8:17 + 2.5	1:14 − 4.0	6:11 − 8.0	9:26 − 5.1
6:12 + 1.7	9:16 + 1.9	2:12 − 4.3	7:16 − 7:3	10:16 − 4.7
7:12 + 2.0	10:12 + 0.7	3:12 − 4.1	8:03 − 6.2	11:10 − 4.2
8:18 + 1.3	11:10 − 1.0	4:14 − 3.6	9:09 − 5.5	12:05 − 4.2
9:08 ± 0.0	12:07 − 2.5	5:18 − 2.6	10:08 − 4.1	1:08 − 3.9
10:18 − 1.0	2:13 − 4.2	6:52 − 0.3	11:03 − 4.0	2:00 − 4.4
11:14 − 2.2	4:16 − 3.4	8:14 + 0.9	2:03 − 4.3	4:11 − 5.5
12:02 − 2.6	6:14 − 0.5	9:09 + 1.1	3:02 − 4.7	6:14 − 7.6
1:10 − 2.8	7:09 + 0.8	10:09 + 0.9	4:04 − 5.2	7:12 − 8.6
2:04 − 2.8	8:21 + 1.3	11:09 − 0.6	5:04 − 5.2	8:13 − 9.0
3:18 − 1.9	9:20 + 0.9	12:12 − 2.3	6:12 − 4.9	9:14 − 9.1
4:06 − 0.7	10:10 + 0.4	2:14 − 5.4	7:58 − 3.1	10:10 − 8.6
5:01 + 0.4	11:04 − 0.8	4:26 − 6.6	9:15 − 1.9	11:08 − 8.5
5:51 + 1.3	12:01 − 2.1	6:06 − 5.0	10:08 − 1.8	12:00 − 7.8
6:56 + 1.8	1:06 − 2.7	7:14 − 3.4	11:02 − 1.8	1:09 − 7.2
8:11 + 1.6	2:17 − 3.3	8:10 − 2.5	12:06 − 2.7	2:11 − 6.6
9:26 + 0.4	3:09 − 2.3	9:04 − 1.7	2:10 − 5.0	3:05 − 6.3
10:15 − 0.7	4:08 − 1.7	10:00 − 1.6	4:12 − 7.9	4:04 − 6.2
11:10 − 2.1	5:02 − 0.6	11:05 − 2.0	6:55 − 8.9	5:07 − 6.1
12:11 − 3.1	5:41 + 0.3	12:00 − 2.8	8:12 − 8.0	6:44 − 6.3
2:12 − 3.2	7:03 + 2.0	1:08 − 3.5	9:10 − 7.4	8:01 − 6.3
4:05 − 1.5	8:06 + 2.7	1:54 − 4.1	10:16 − 6.5	9:03 − 6.5
6:10 + 0.7	9:05 + 2.4	3:20 − 4.9	11:10 − 6.3	10:08 − 6.3
7:40 + 1.1	10:06 + 0.9	4:10 − 4.4	12:02 − 6.0	12:09 − 5.3
8:46 + 0.6	11:02 − 0.5	5:10 − 3.5	1:07 − 6.5	1:56 − 4.9
9:46 − 1.0	12:05 − 2.6	5:49 − 2.7	2:08 − 6.8	4:08 − 4.9
10:52 − 1.3	3:31 − 5.2	7:14 − 0.9	3:17 − 7.1	6:06 − 6.5
11:53 − 2.3	5:10 − 4.5	8:10 + 0.2	4:07 − 7.1	7:21 − 7.9
12:51 − 2.8	6:39 − 1.3	9:08 + 0.7	5:06 − 7.3	8:34 − 8.7
2:10 − 2.8	8:18 ± 0.0	10:23 + 0.3	5:53 − 7.0	9:26 − 9.1
2:52 − 2.3	9:11 + 0.2	11:20 − 0.6	6:58 − 6.6	10:16 − 8.8
4:01 − 1.0	10:12 − 0.2	12:20 − 2.6	8:08 − 6.1	11:09 − 8.4
5:06 + 0.2	11:05 − 0.8	2:06 − 5.3	9:16 − 4.7	11:56 − 7.8
6:21 + 1.8	12:04 − 1.8	5:00 − 7.6	10:20 − 4.6	1:07 − 7.0
8:12 + 2.0	1:08 − 2.7	5:58 − 7.2	11:16 − 4.1	2:07 − 6.2
9:22 + 0.9	2:03 − 3.3	7:06 − 6.1	12:09 − 4.3	3:26 − 5.7
10:06 − 0.2	3:15 − 3.3	8:05 − 5.0	2:13 − 5.8	4:12 − 5.3
11:17 − 2.0	4:10 − 2.5	9:08 − 3.7	4:23 − 7.8	5:00 − 5.2
12:14 − 3.4	5:08 − 1.3	10:06 − 2.9	6:28 − 9.8	5:46 − 5.1
1:58 − 4.1	5:49 − 0.5	11:10 − 2.8	7:56 −10.0	7:00 − 5.6
4:26 − 2.2	7:37 + 1.8	12:02 − 2.8	9:02 −10.1	8:00 − 6.1
6:59 + 0.9	8:43 + 2.1	1:18 − 3.4	10:12 − 9.8	9:16 − 6.7
8:14 + 1.4	10:12 + 1.2	2:15 − 4.4	C= +1.30	10:18 − 6.8
9:11 + 1.1	11:16 − 0.6	3:11 − 4.0	11:21 − 8.7	11:07 − 6.8
10:13 + 0.2	12:03 − 2.2	4:04 − 4.4	12:04 − 7.6	12:24 − 6.3
11:10 − 1.1	2:06 − 5.4	4:58 − 4.1	1:08 − 7.1	2:03 − 5.2
12:10 − 1.8	4:16 − 6.0	5:48 − 3.7		4:19 − 4.1

TABLE III—*Continued*

A.M. October 24	P.M. October 26	A.M. October 29	A.M. November 1	P.M. November 3
6:06 — 5.3	6:29 — 2.8	9:10 — 4.2	12:42 — 5.3	2:11 — 4.2
7:07 — 6.2	8:05 — 3.6	10:08 — 5.0	2:20 — 8.3	3:15 — 4.3
8:11 — 7.3	9:17 — 5.1	11:12 — 6.0	4:12 — 9.9	4:10 — 3.8
9:08 — 8.2	10:16 — 6.9	12:08 — 6.9	6:06 — 9.3	5:12 — 3.7
10:05 — 9.1	12:11 — 9.6	1:10 — 8.1	7:12 — 8.8	5:50 — 3.8
11:04 — 9.3	2:02 — 9.8	2:14 — 8.0	**C = −2.64**	6:52 — 3.6
11:55 — 8.6	4:10 — 7.2	3:18 — 7.5		8:16 — 2.3
1:09 — 7.9	6:00 — 4.5	4:13 — 6.2	8:08 — 7.3	9:19 — 1.7
2:10 — 6.5	7:20 — 4.2	5:08 — 4.7	9:04 — 5.6	10:20 — 0.9
3:04 — 5.6	8:16 — 4.4	5:51 — 3.5	10:15 — 5.0	11:14 — 0.7
4:08 — 4.5	9:21 — 5.4	6:58 — 1.8	11:16 — 4.6	12:10 — 0.4
5:05 — 4.1	10:15 — 6.4	8:08 — 1.2	12:02 — 4.8	2:17 — 1.5
5:56 — 3.8	11:07 — 7.6	9:24 — 1.5	1:06 — 5.0	**C = −1.84**
6:56 — 4.4	12:02 — 8.6	10:21 — 2.9	2:09 — 5.9	
8:12 — 5.1	1:00 — 9.0	11:16 — 5.0	3:15 — 6.1	4:16 — 2.9
9:04 — 6.0	2:16 — 8.4	12:14 — 6.9	4:16 — 6.3	6:17 — 4.6
10:10 — 6.9	3:12 — 7.1	2:15 —10.7	5:20 — 6.0	7:19 — 5.2
11:16 — 7.5	4:16 — 5.5	4:16 —10.8	5:53 — 5.3	8:18 — 5.2
12:23 — 7.2	5:14 — 3.5	6:14 — 8.2	6:54 — 4.1	9:11 — 4.9
2:06 — 6.2	5:52 — 2.6	7:14 — 7.0	8:12 — 2.4	10:13 — 4.9
4:16 — 4.2	6:49 — 2.0	9:16 — 5.4	9:14 — 1.2	11:16 — 4.1
6:16 — 3.5	8:15 — 2.0	12:09 — 7.0	10:17 — 1.0	12:04 — 4.1
7:13 — 4.4	9:09 — 3.3	1:08 — 8.0	11:21 — 1.3	1:11 — 3.4
8:10 — 5.5	10:08 — 4.9	2:05 — 8.7	12:36 — 2.6	2:16 — 3.0
9:25 — 6.7	11:12 — 7.3	3:16 — 8.3	2:19 — 5.1	3:17 — 2.7
10:22 — 7.6	12:08 — 9.1	4:15 — 7.3	4:17 — 7.4	3:28 — 2.2
11:14 — 7.9	2:13 —10.5	5:08 — 6.2	6:14 — 8.3	4:18 — 2.6
12:01 — 7.9	4:12 — 8.3	5:56 — 4.6	8:17 — 6.1	5:07 — 2.6
1:08 — 7.2	6:49 — 4.2	6:58 — 3.3	9:19 — 5.5	5:54 — 2.3
2:10 — 6.1	7:30 — 3.8	8:13 — 1.6	10:17 — 4.8	6:50 — 1.8
3:20 — 4.5	8:18 — 3.5	9:18 — 1.6	11:10 — 4.3	8:05 — 1.7
4:19 — 3.6	9:06 — 3.6	10:18 — 2.3	12:15 — 4.2	9:14 — 1.5
5:09 — 2.7	10:06 — 4.4	11:20 — 3.7	1:18 — 4.2	10:09 — 1.1
5:53 — 2.4	11:07 — 5.4	12:33 — 6.0	2:25 — 5.0	11:10 — 0.6
7:08 — 2.7	12:02 — 7.0	2:16 — 9.4	3:15 — 4.7	12:23 — 0.3
8:02 — 3.7	1:14 — 7.6	4:16 —10.6	4:14 — 4.7	2:12 — 0.6
9:13 — 5.0	**C = +0.90**	6:25 — 8.9	5:18 — 4.5	4:11 — 1.7
10:17 — 6.7		7:18 — 7.9	6:24 — 3.5	6:12 — 3.4
11:12 — 7.5	3:06 — 8.8	8:27 — 6.5	8:04 — 2.4	7:12 — 3.7
12:02 — 7.9	3:48 — 7.9	9:34 — 5.8	9:16 — 1.2	8:15 — 4.1
2:19 — 7.0	4:46 — 5.7	10:17 — 5.6	10:06 — 0.7	9:16 — 4.6
4:12 — 4.5	5:20 — 4.4	11:12 — 6.0	11:09 — 0.9	10:27 — 4.4
6:14 — 3.1	5:49 — 3.2	12:04 — 6.3	12:16 — 1.4	11:08 — 4.5
7:14 — 3.6	6:54 — 2.2	1:05 — 7.0	2:17 — 3.2	12:04 — 3.6
8:16 — 4.3	8:07 — 1.7	2:29 — 7.5	4:38 — 5.6	1:12 — 2.7
9:16 — 5.9	9:06 — 2.7	3:31 — 7.2	6:24 — 6.5	2:12 — 2.4
10:15 — 7.3	10:10 — 4.2	4:20 — 7.1	8:19 — 5.9	3:10 — 1.6
11:13 — 8.7	11:19 — 6.4	5:13 — 6.0	**C = −0.84**	4:04 — 0.9
12:09 — 9.2	12:18 — 8.4	5:56 — 4.9		5:04 — 0.9
1:14 — 8.9	2:11 —10.5	6:52 — 3.6	9:26 — 5.7	5:52 — 1.4
2:28 — 8.1	4:08 —10.1	8:22 — 2.0	10:10 — 5.0	6:51 — 1.3
3:27 — 6.7	6:10 — 6.7	9:19 — 1.3	11:12 — 4.7	8:00 — 1.5
4:14 — 5.5	7:18 — 4.9	10:10 — 1.8	12:06 — 4.2	9:45 — 1.7
5:21 — 3.5	8:18 — 4.2	11:30 — 2.8	1:08 — 4.4	11:04 — 1.4

TABLE III—*Continued*

A.M. November 6	P.M. November 8	A.M. November 11	P.M. November 13	P.M. November 16
1:04 − 0.9	12:06 − 3.0	8:27 + 0.4	8:00 + 5.8	1:17 + 1.5
2:19 − 0.1	1:05 − 2.4	9:23 − 0.6	9:10 + 5.4	2:30 + 1.1
4:19 − 0.7	2:13 − 1.4	10:14 − 1.6	10:07 + 4.0	3:17 + 1.0
6:17 − 1.8	3:14 − 0.5	11:10 − 2.4	11:08 + 2.2	4:06 + 1.2
7:12 − 1.7	4:18 + 0.7	12:04 − 2.8	12:08 + 0.3	5:12 + 2.3
8:04 − 2.7	5:10 + 0.8	1:04 − 2.7	2:10 − 2.5	6:24 + 4.2
9:05 − 3.5	5:55 + 1.5	1:55 − 2.6	4:16 − 2.6	8:00 + 5.7
10:07 − 4.3	6:55 + 1.6	3:08 − 1.0	6:38 + 0.1	9:17 + 6.4
11:07 − 3.9	8:03 + 0.9	4:18 + 0.7	8:06 + 1.7	10:16 + 6.7
12:07 − 3.5	9:11 − 0.3	5:11 + 1.9	9:13 + 2.3	11:06 + 6.1
1:19 − 2.8	10:10 − 1.2	5:56 + 3.1	10:10 + 2.0	12:19 + 4.5
2:12 − 1.8	11:18 − 2.3	6:59 + 3.8	11:09 + 1.5	2:07 + 1.8
3:08 − 1.5	12:20 − 2.6	8:10 + 3.8	12:07 + 0.8	4:38 − 1.4
4:06 − 0.2	2:10 − 1.8	9:11 + 2.3	1:08 − 0.4	7:22 − 0.1
5:06 ± 0.0	4:17 − 0.1	10:12 + 0.8	2:01 − 0.4	8:15 + 0.5
5:50 − 0.2	6:18 + 1.0	11:10 − 0.7	3:09 + 0.5	9:10 + 1.5
6:48 − 0.4	7:08 + 1.0	12:32 − 2.6	4:09 + 1.3	10:12 + 2.4
7:59 − 0.9	8:15 + 0.2	2:08 − 3.4	5:06 + 2.6	11:14 + 2.8
9:08 − 0.9	9:16 − 0.6	4:10 − 2.5	5:56 + 3.5	12:10 + 2.6
10:10 − 1.8	10:16 − 1.9	6:28 + 0.8	6:50 + 4.6	1:07 + 2.5
11:08 − 1.7	11:16 − 2.4	7:24 + 1.4	8:12 + 6.1	2:10 + 1.8
12:14 − 1.4	1:13 − 2.7	8:16 + 1.3	9:12 + 5.8	3:15 + 1.7
1:11 − 0.8	2:29 − 1.5	9:18 + 0.8	10:20 + 5.1	4:03 + 1.6
2:10 − 0.3	3:27 − 0.3	10:14 + 0.1	11:14 + 3.9	5:05 + 2.3
4:18 + 0.4	4:36 + 1.3	11:18 − 1.0	12:04 + 2.3	5:52 + 2.6
6:12 − 0.3	5:25 + 1.8	12:08 − 1.4	2:11 − 1.9	7:12 + 3.9
7:12 − 0.7	6:13 + 2.1	1:08 − 1.7	4:16 − 2.4	8:08 + 4.8
8:08 − 1.1	8:25 + 1.4	2:12 − 1.7	6:08 − 0.6	
9:13 − 2.4	9:18 − 0.1	3:10 − 0.7	7:58 + 1.8	**C = +2.66**
10:09 − 2.5	10:18 − 1.1	4:04 + 1.1	9:06 + 2.6	9:16 + 5.7
11:05 − 3.3	11:20 − 2.6	5:05 + 2.8	10:18 + 2.5	10:09 + 6.3
12:04 − 3.0	12:20 − 3.3	6:00 + 3.7	11:08 + 2.3	11:09 + 6.4
1:07 − 2.2	2:04 − 3.2	7:05 + 4.7	12:04 + 1.7	12:12 + 5.7
2:22 − 1.3	4:08 − 0.3	8:08 + 4.9	1:12 + 1.1	2:08 + 3.4
3:12 − 0.7	6:04 + 1.1	9:17 + 3.9	2:16 + 0.6	4:12 + 0.4
4:17 + 0.3	8:20 + 1.0	10:08 + 3.0	3:16 + 0.7	6:13 − 0.2
	9:32 − 0.2	11:08 + 1.0	4:11 + 0.8	7:30 ± 0.0
C = −2.83	10:51 − 1.5	12:15 − 1.0	5:16 + 2.4	8:23 + 0.9
5:12 + 0.5	12:07 − 2.4	2:27 − 3.2	5:57 + 3.5	9:19 + 1.7
5:56 + 1.0	1:10 − 2.2	4:18 − 2.0	6:51 + 4.7	10:14 + 2.1
6:52 + 1.1	2:08 − 1.4	6:12 − 0.1	8:17 + 6.4	11:10 + 2.4
7:48 + 0.2	3:08 − 0.2	7:30 + 1.6	9:13 + 6.4	12:03 + 3.1
9:16 − 0.4	4:20 + 1.3	8:26 + 2.2	10:08 + 6.3	1:12 + 3.2
10:10 − 1.7	5:16 + 2.9	9:23 + 2.0	11:05 + 5.2	2:08 + 3.0
11:13 − 2.0	5:52 + 2.9	10:12 + 1.3	12:18 + 3.1	3:05 + 2.0?
12:13 − 2.1	6:52 + 3.3	11:06 + 0.5	2:06 − 0.1	4:04 + 2.7
2:44 − 0.9	9:01 + 1.6	12:06 ± 0.0	4:22 − 1.9	5:04 + 3.4
4:24 + 0.1	10:10 + 0.4	1:03 − 0.7	6:14 − 0.8	5:53 + 3.1
6:13 + 0.2	11:13 − 1.3	2:04 − 0.6	7:12 + 0.2	6:49 + 4.0
7:22 − 0.3	12:26 − 3.4	3:12 + 0.3	8:12 + 0.9	8:08 + 5.3
8:16 − 1.1	2:10 − 3.7	4:10 + 1.3	9:09 + 1.7	9:24 + 6.2
9:12 − 1.6	4:18 − 1.8	5:15 + 2.8	10:13 + 2.5	10:11 + 6.9
10:10 − 2.3	6:14 + 0.5	5:58 + 4.0	11:10 + 2.4	11:10 + 7.4
11:09 − 3.1	7:20 + 0.8	6:50 + 4.8	12:15 + 2.2	12:11 + 7.3

TABLE III—*Continued*

A.M. November 19	A.M. November 21	A.M. November 23	A.M. November 25	A.M. November 27
2:14 + 5.8	4:12 + 6.8	6:12 + 7.0	10:06 + 4.8	11:06 + 6.3
4:15 + 3.7	6:04 + 4.8	7:11 + 6.1	11:04 + 3.8	12:08 + 5.5
6:16 + 1.7	7:15 + 4.0	8:10 + 5.1	12:06 + 3.4	12:48 + 5.2
7:16 + 1.3	8:12 + 3.4	9:10 + 3.9	1:05 + 3.6	2:05 + 4.9
8:08 + 1.3	9:09 + 3.1	10:12 + 3.2	2:05 + 4.4	3:17 + 6.2
9:21 + 2.0	10:08 + 3.2	11:08 + 2.9	3:09 + 5.9	4:17 + 7.4
10:12 + 2.4	11:12 + 3.5	12:08 + 3.4	4:10 + 7.6	5:12 + 9.1
11:08 + 3.0	12:06 + 4.3	1:12 + 4.4	5:08 + 9.0	6:17 +10.6
12:12 + 3.7	1:09 + 5.4	2:18 + 6.0	5:55 + 9.7	7:30 +11.9
1:23 + 4.0	2:10 + 6.3	3:08 + 7.1	6:54 +10.0	8:16 +11.8
2:25 + 4.1	3:03 + 7.4	4:07 + 8.4	8:10 + 8.8	9:28 +11.0
3:12 + 4.2	4:09 + 7.8	5:03 + 8.6	9:08 + 7.7	10:18 + 9.6
4:14 + 4.1	5:14 + 7.8	6:08 + 8.7	10:05 + 6.0	11:08 + 7.9
5:13 + 4.1	5:50 + 7.2	8:02 + 6.9	11:08 + 4.0	12:09 + 5.9
5:50 + 4.0	6:53 + 6.6	9:06 + 5.1	12:08 + 2.5	2:03 + 2.7
7:06 + 4.3	8:06 + 5.6	10:09 + 3.8	2:10 + 1.1	3:52 + 2.4
8:11 + 4.4	9:16 + 5.1	1:15 + 2.8	4:05 + 2.8	5:35 + 4.1
9:19 + 5.3	10:14 + 5.0	3:07 + 4.5	5:56 + 5.7	6:37 + 5.6
10:12 + 5.7	11:14 + 5.3	5:06 + 6.5	7:18 + 6.9	8:19 + 7.4
11:05 + 6.3	12:12 + 5.6	7:11 + 6.4	8:20 + 7.1	9:06 + 7.6
12:16 + 6.8	2:34 + 6.8	8:18 + 5.6	9:18 + 6.4	10:04 + 7.6
2:09 + 5.9	4:10 + 7.3	9:18 + 4.4	10:16 + 5.7	11:06 + 7.2
4:12 + 4.5	6:10 + 6.2	10:07 + 3.6	11:09 + 4.7	12:06 + 6.2
6:07 + 2.7	7:20 + 5.1	11:14 + 3.1	12:06 + 4.1	1:07 + 5.7
7:14 + 1.9	8:12 + 4.3	12:04 + 2.9	1:02 + 3.9	2:08 + 5.2
8:08 + 1.6	9:08 + 3.5	1:10 + 3.6	2:06 + 4.7	3:16 + 5.8
9:22 + 1.8	10:14 + 3.2	2:07 + 4.8	3:10 + 6.0	4:08 + 6.6
10:18 + 2.1	11:09 + 3.3	3:19 + 6.9	4:08 + 7.4	5:05 + 7.9
11:09 + 2.9	12:02 + 3.7	4:14 + 8.3	5:06 + 9.3	5:48 + 9.0
12:09 + 3.4	1:09 + 4.9	5:09 + 9.4	6:00 +10.3	6:56 +10.8
1:05 + 4.3	2:14 + 5.9	6:00 + 9.6	6:52 +11.0	7:54 +11.8
2:04 + 4.7	3:18 + 7.4	6:54 + 9.2	8:02 +11.0	8:44 +11.9
3:07 + 5.3	4:14 + 8.0	8:12 + 8.3	9:10 +10.0	10:03 +11.2
4:05 + 5.2	5:08 + 8.4	9:10 + 6.8	10:12 + 8.1	12:00 + 7.8
5:03 + 5.3	5:52 + 8.2	10:13 + 5.1	11:18 + 5.9	3:15 + 2.6
5:56 + 4.9	6:48 + 7.5	11:05 + 3.4	12:36 + 3.4	5:16 + 3.0
6:56 + 4.8	8:02 + 6.5	12:08 + 2.2	2:08 + 1.8	7:06 + 5.3
8:04 + 4.8	9:20 + 5.1	2:12 + 2.5	4:26 + 3.1	8:21 + 6.9
9:08 + 5.2	10:06 + 4.3	4:16 + 4.7	6:04 + 5.2	9:30 + 7.8
10:14 + 5.4	11:17 + 3.7	6:10 + 6.9	7:16 + 6.7	10:48 + 7.5
11:07 + 6.0	12:18 + 4.1	7:20 + 6.9	8:21 + 7.5	12:03 + 7.0
12:12 + 6.6	2:12 + 5.6	8:24 + 6.4	9:18 + 7.4	1:22 + 6.2
2:06 + 7.2	4:12 + 7.0	9:14 + 5.6	10:04 + 7.0	2:18 + 6.0

TABLE IV 10(S.−N.+C.)

A.M. September 27	P.M. September 29	P.M. October 2	A.M. October 5	P.M. October 7
C=+0.70	9:36 + 0.8	3:59 − 3.6	9:01 − 6.8	10:01 − 8.1
8:04 + 2.9	11:01 + 1.6	5:01 − 4.6	10:02 − 7.0	11:00 − 8.4
9:00 + 3.2	11:59 + 1.9	5:59 − 5.3	**C=−2.30**	11:55 − 8.5
10:00 + 3.3	2:00 + 0.9	7:02 − 5.8	11:51 − 6.3	2:06 − 9.0
11:04 + 3.2	3:00 − 0.9	8:00 − 5.5	12:52 − 6.1	6:20 − 7.9
12:06 + 1.9	4:02 − 2.2	8:58 − 4.9	2:37 − 6.8	6:54 − 7.6
12:58 + 0.6	5:02 − 2.8	10:20 − 3.6	3:56 − 7.3	7:56 − 7.6
2:00 − 0.9	6:06 − 2.8	11:17 − 3.2	5:08 − 6.9	8:58 − 7.7
2:58 − 1.8	7:10 − 2.9	12:19 − 2.3	6:18 − 7.4	10:12 − 7.9
3:56 − 3.0	8:09 − 1.9	1:51 − 2.5	7:55 − 8.2	11:06 − 8.5
5:03 − 2.2	9:43 ± 0.0	3:05 − 2.8	9:12 − 8.0	12:06 − 9.2
5:58 − 0.9	10:52 + 0.4	4:04 − 3.6	10:18 − 8.6	1:00 − 9.4
6:54 − 0.1	2:08 − 0.1	6:29 − 5.6	11:55 − 8.7	1:59 − 9.3
8:02 + 0.7	3:10 − 1.9	7:49 − 6.1	2:12 − 8.1	3:01 − 9.1
9:03 + 2.0	4:05 − 3.2	8:58 − 6.2	4:02 − 7.9	3:58 − 9.1
C=+0.80	5:02 − 3.9	10:12 − 5.8	6:20 − 8.2	5:01 − 8.6
10:13 + 2.8	6:04 − 4.2	10:56 − 4.9	8:24 − 8.2	6:00 − 8.4
11:01 + 2.7	6:57 − 3.8	12:16 − 4.1	9:08 − 8.4	6:56 − 7.9
12:02 + 1.9	8:06 − 2.7	1:10 − 3.6	10:09 − 8.8	7:58 − 7.7
1:52 − 0.1	10:20 − 1.0	2:04 − 3.4	11:12 − 8.5	9:15 − 7.6
3:48 − 2.0	1:31 − 0.7	3:04 − 3.5	12:24 − 9.0	10:26 − 7.9
5:56 − 1.2	3:14 − 1.4	4:05 − 4.0	1:15 − 9.1	12:12 − 8.5
9:18 + 1.5	4:06 − 3.2	4:54 − 4.7	2:08 − 9.0	1:45 − 9.1
10:18 + 2.6	5:13 − 4.0	5:58 − 5.2	3:09 − 8.9	4:08 − 9.3
11:04 + 2.5	6:18 − 5.0	6:50 − 5.7	4:04 − 8.5	6:00 − 8.7
12:13 + 1.9	7:24 − 4.7	**C=+1.10**	**C=−1.76**	6:58 − 7.6
1:26 + 0.7	8:25 − 3.6	8:08 − 6.0	4:53 − 8.5	7:54 − 7.5
2:32 − 1.3	10:48 − 1.7	9:37 − 5.0	6:04 − 8.0	9:04 − 7.4
3:23 − 2.3	12:10 − 0.9	11:04 − 4.4	6:52 − 8.1	9:56 − 7.9
4:03 − 2.3	1:22 − 1.5	11:56 − 3.8	8:14 − 7.9	11:02 − 8.6
4:54 − 2.5	3:08 − 3.2	2:28 − 3.9	9:08 − 8.1	12:16 −10.0
6:00 − 1.6	4:00 − 3.5	5:33 − 5.1	10:05 − 7.9	12:58 −10.1
6:56 − 0.7	5:04 − 4.3	7:52 − 5.7	10:58 − 8.8	2:23 −10.4
7:54 + 0.6	6:02 − 4.5	8:58 − 6.0	11:55 − 8.9	2:57 −10.5
8:56 + 2.0	7:04 − 5.7?	10:01 − 6.3	1:56 − 8.5	4:07 −10.5
10:04 + 2.5	8:15 − 6.1?	11:11 − 6.7	4:07 − 8.2	5:05 − 9.9
11:12 + 3.4	9:08 − 3.8	12:06 − 5.9	6:09 − 8.0	6:02 − 9.2
12:04 + 2.6	**C=+1.92**	1:14 − 5.5	6:56 − 7.5	6:52 − 8.7
1:57 − 0.1	10:03 − 2.4	2:00 − 5.2	8:12 − 8.3	8:02 − 7.9
4:06 − 2.0	11:03 − 1.0	3:15 − 4.9	9:04 − 8.1	9:15 − 7.5
8:07 − 0.3	12:00 − 1.0	4:01 − 4.9	10:08 − 8.9	9:58 − 7.3
9:03 + 0.4	1:57 − 1.2	4:53 − 5.3	11:06 − 9.4	11:03 − 7.8
9:58 + 1.6	4:01 − 3.4	5:47 − 5.7	12:12 − 9.6	12:11 − 8.4
11:10 + 1.8	6:14 − 4.7	7:04 − 6.1	12:56 − 9.6	2:00 − 9.5
12:09 + 1.6	7:06 − 5.0	7:53 − 6.1	2:00 − 9.7	4:12 −10.2
1:11 + 0.1	8:12 − 5.3	8:56 − 6.4	2:55 −10.0	6:04 − 9.2
1:56 ± 0.0	9:01 − 5.0	10:04 − 6.7	4:01 − 8.5	7:09 − 8.8
2:58 − 1.4	9:57 − 4.4	10:56 − 6.6	4:56 − 8.6	8:02 − 8.2
4:05 − 2.2	11:06 − 3.7	12:02 − 6.1	5:51 − 8.0	8:58 − 8.0
5:07 − 2.8	12:10 − 2.6	2:00 − 5.7	7:07 − 7.7	10:00 − 8.0
5:52 − 2.3	1:00 − 2.4	4:09 − 5.6	7:58 − 7.5	10:59 − 8.3
7:04 − 2.5	2:12 − 2.3	6:28 − 6.5	8:56 − 7.7	12:11 − 9.3
8:19 − 0.8	3:10 − 3.2	7:30 − 5.9		12:58 −10.0
				1:56 −10.2

TABLE IV—*Continued*

P.M. October 10	A.M. October 13	P.M. October 15	P.M. October 18	P.M. October 21
3:02 −10.4	9:04 − 7.3	11:08 − 6.6	3:04 − 9.3	12:11 −11.6
4:03 −10.4	10:05 − 6.9	11:54 − 6.7	3:55 − 9.8	12:57 −11.1
5:02 −10.1	11:03 − 6.6	1:56 − 7.3	4:50 −10.1	2:03 −10.9
6:07 − 9.4	12:16 − 6.8	4:07 − 8.9	5:58 −10.6	3:10 −10.2
6:46 − 8.4	1:09 − 7.4	5:53 −10.1	6:42 −10.8	4:00 −10.1
8:01 − 8.0	2:16 − 8.4	7:05 − 9.5	8:19 −11.0	4:56 −10.4
9:10 − 7.1	3:04 − 9.2	7:55 − 9.2	9:42 −10.5	5:52 −10.5
10:06 − 7.1	4:06 −10.1	8:58 − 8.1	10:52 − 9.8	6:52 −10.7
11:02 − 7.7	5:02 − 9.5	10:02 − 7.1	11:52 − 9.7	7:53 −11.1
12:26 − 8.1	6:08 − 9.1	10:58 − 6.9	1:54 − 9.0	9:17 −11.6
2:00 − 8.8	6:44 − 8.9	12:12 − 6.8	3:54 − 9.9	10:06 −11.7
4:00 − 9.3	8:06 − 7.4	1:07 − 6.9	5:59 −10.1	11:01 −12.0
6:01 − 8.3	9:08 − 6.5	2:04 − 7.6	7:05 −11.4	11:54 −12.0
7:02 − 7.9	10:02 − 5.8	3:04 − 8.2	8:15 −11.8	12:58 −11.8
8:08 − 6.7	11:00 − 5.5	4:06 − 9.2	9:00 −12.3	1:50 −11.8
8:58 − 6.7	11:58 − 5.6	5:08 −10.2	9:59 −11.8	4:00 −11.7
10:09 − 6.3	2:02 − 7.6	6:38 −10.3	10:54 −10.9	6:05 −11.7
11:06 − 6.5	4:02 − 9.1	8:02 − 9.9	1:56 − 9.4	7:00 −11.8
12:12 − 7.1	6:03 − 9.2	8:56 − 9.4	2:54 − 9.4	8:04 −12.3
1:02 − 7.5	6:58 − 8.3	9:59 − 8.5	3:56 − 9.7	9:05 −12.9
1:54 − 8.0	8:13 − 7.5	10:58 − 7.7	4:56 −10.1	10:01 −13.0
3:10 − 8.8	9:12 − 7.1	12:00 − 7.6	6:22 −10.7	10:59 −13.4
4:00 − 9.1	10:02 − 6.4	2:02 − 8.4	7:50 −11.9	12:10 −13.2
4:55 − 8.8	10:56 − 6.4	4:16 −10.3	9:06 −11.8	1:00 −13.2
6:02 − 8.3	12:10 − 6.7	5:56 −11.1	9:59 −11.2	2:00 −12.7
6:49 − 7.7	12:58 − 7.2	7:08 −11.5	10:54 −10.8	2:57 −12.7
8:00 − 6.6	2:10 − 8.1	8:02 −10.9	11:58 −10.4	3:57 −12.3
9:18 − 5.7	3:00 − 9.3	8:55 −10.4	2:02 − 9.5	4:59 −12.0
10:08 − 5.5	4:00 −10.1	9:52 − 9.9	4:04 − 9.7	5:55 −11.8
11:03 − 5.4	4:53 −10.0	10:58 − 9.1	6:46 −10.9	6:54 −11.9
12:03 − 5.9	5:55 −10.0	12:09 − 8.5	8:03 −11.4	7:52 −11.9
2:00 − 7.3	6:53 − 9.6	12:58 − 8.2	9:04 −11.3	8:55 −12.2
3:55 − 8.6	7:58 − 8.9	2:03 − 8.3	10:10 −10.9	9.59 −12.6
6:00 − 8.1	8:55 − 7.7	3:07 − 9.3	11:02 −10.5	12:02 −13.3
7:28 − 6.8	9:55 − 6.8	4:02 −10.1	12:08 −10.0	1:47 −13.4
8:34 − 6.2	10:52 − 6.4	5:00 −10.8	12:54 − 9.5	4:00 −12.9
9:38 − 6.0	11:54 − 6.2	5:59 −11.4	2:00 − 9.1	5:56 −12.1
10:43 − 5.8	3:22 − 8.7	7:04 −11.4	3:10 − 9.2	7:12 −12.2
11:44 − 6.0	5:02 −10.2	8:00 −11.3	3:58 − 9.4	8:24 −12.5
12:44 − 6.6	6:31 −10.1	8:55 −10.6	4:56 − 9.7	9:11 −13.2
2:02 − 8.0	8:10 − 9.2	10:12 −10.0	6:02 −10.0	10:03 −13.4
2:46 − 8.8	9:03 − 8.6	11:07 − 8.9	6:48 −10.3	11:00 −14.1
3:54 − 9.1	10:04 − 7.9	12:11 − 8.5	7:58 −10.6	11:48 −14.2
4:58 − 8.9	10:58 − 7.6	1:54 − 8.1	9:04 −11.3	12:58 −14.1
6:14 − 8.2	12:12 − 7.4	4:50 −10.1	10:10 −11.2	1:58 −14.1
8:20 − 6.5	12:58 − 8.0	5:47 −10.7	11:05 −11.0	3:18 −12.8
9:14 − 6.2	1:54 − 8.3	6:58 −11.0	11:58 −10.9	4:02 −12.7
9:59 − 5.8	3:08 − 9.4	7:57 −11.2	2:02 −10.2	4:53 −12.2
11:10 − 5.4	4:03 −10.0	9:00 −11.1	4:09 −10.0	5:54 −11.6
12:06 − 5.7	5:02 −10.6	9:57 −10.3	6:14 −10.4	6:52 −11.4
1:51 − 7.3	5:58 −10.9	11:02 − 9.6	7:43 −11.1	7:54 −11.1
4:17 − 9.0	7:12 −10.3	12:10 − 9.1	8:52 −11.1	9:09 −11.2
6:50 − 8.4	8:36 − 8.6	1:12 − 8.6	10:01 −11.6	10:11 −11.9
8:07 − 7.6	10:02 − 7.4	2:07 − 8.8	11:06 −11.3	11:00 −12.5

TABLE IV—*Continued*

A.M. October 24	P.M. October 26	A.M. October 29	P.M. October 31	A.M. November 3
12:16 −13.2	3:17 −16.0	9:01 −17.5	5:04 −21.1	11:03 −21.7
1:55 −13.9	4:07 −16.0	10:00 −16.7	5:47 −21.5	12:14 −21.3
4:09 −13.6	5:14 −15.7	11:04 −16.3	6:44 −22.1	12:58 −21.5
5:56 −12.5	6:35 −14.7	12:18 −16.3	8:13 −21.9	2:04 −21.0
6:58 −12.0	8:16 −13.1	12:56 −17.0	9:08 −21.1	3:07 −20.6
8:03 −11.9	9:10 −12.4	C=−1.60	10:00 −20.8	4:02 −20.9
9:00 −12.4	10:09 −12.4		11:19 −19.9	5:04 −21.1
9:56 −12.5	12:04 −13.5	2:03 −17.9	12:34 −19.4	5:58 −21.5
10:54 −13.3	1:54 −15.6	3:05 −19.6	2:10 −19.2	6:44 −21.8
12:04 −14.3	4:01 −16.9	4:01 −20.4	4:02 −20.3	8:07 −22.4
12:59 −14.7	5:52 −16.3	5:00 −21.4	5:57 −21.6	9:07 −22.4
2:00 −15.0	7:12 −14.9	5:42 −21.7	7:18 −22.2	10:11 −22.4
2:56 −14.7	8:08 −14.1	6:48 −21.4	7:58 −22.3	11:06 −22.1
4:00 −14.1	9:16 −13.3	7:56 −20.9	8:54 −22.3	12:00 −22.3
4:55 −13.3	10:07 −13.1	9:10 −19.7	10:04 −21.4	2:06 −21.9
6:05 −12.6	11:00 −13.2	10:10 −18.4	11:08 −20.5	4:07 −22.0
6:48 −12.4	12:10 −13.9	11:04 −18.1	12:10 −19.8	6:06 −22.2
8:00 −11.8	12:52 −14.6	12:02 −18.2	1:02 −19.4	7:08 −22.6
8:55 −11.5	2:07 −15.8	C=+0.60	2:00 −19.5	8:11 −22.8
10:02 −11.8	3:03 −16.8		3:02 −19.6	9:02 −22.9
11:08 −12.6	4:08 −17.5	2:04 −19.6	4:04 −20.4	10:03 −23.1
12:16 −13.6	5:07 −17.3	4:08 −21.2	5:09 −21.1	11:08 −22.9
1:57 −14.7	6:01 −16.9	6:04 −22.2	6:02 −22.0	11:56 −22.9
4:04 −14.1	6:42 −16.5	7:05 −21.9	6:45 −22.5	1:05 −22.6
6:00 −13.2	8:04 −15.4	8:04 −21.1	8:00 −22.4	2:08 −22.5
7:03 −12.5	8:58 −14.3	9:26 −19.8	9:04 −22.5	3:09 −22.1
8:00 −12.2	9:56 −13.7	10:19 −18.9	10:06 −21.8	3:19 −21.9
9:17 −12.5	10:58 −13.7	11:06 −18.4	11:10 −21.2	4:08 −21.6
10:14 −13.0	11:58 −14.0	12:17 −18.3	12:25 −20.9	4:58 −21.4
11:05 −13.5	2:00 −16.6	12:56 −18.5	2:06 −20.2	6:02 −21.5
11:53 −14.4	4:02 −18.3	1:58 −19.0	4:05 −21.1	6:41 −21.7
12:59 −15.0	6:37 −17.8	3:02 −20.2	6:01 −21.8	7:57 −21.9
2:01 −15.8	7:20 −16.9	4:05 −21.5	8:04 −22.4	9:07 −22.2
3:12 −15.7	8:10 −16.2	4:59 −22.2	9:04 −22.5	10:00 −22.4
4:11 −15.1	8:59 −15.4	5:47 −22.6	10:09 −22.1	11:02 −22.5
5:00 −14.5	9:58 −14.9	6:48 −22.7	11:01 −21.6	12:14 −22.6
6:00 −13.9	10:59 −14.8	8:00 −22.0	12:08 −21.4	2:03 −22.3
7:01 −13.0	12:09 −15.0	9:08 −21.5	1:09 −20.8	4:00 −22.0
8:08 −12.0	1:05 −15.9	10:08 −20.6	2:17 −20.5	6:01 −22.0
9:06 −11.7	4:05 −20.2	11:10 −20.1	3:06 −20.8	7:02 −21.9
10:10 −11.9	4:34 −20.7	12:21 −19.7	4:06 −21.0	8:06 −22.2
11:04 −12.5	5:10 −20.2	2:08 −20.1	5:07 −21.7	9:02 −22.4
11:54 −13.2	5:40 −20.2	4:07 −21.8	6:34 −22.4	10:15 −22.5
2:06 −15.4	6:44 −19.5	6:17 −23.5	7:56 −22.9	10:59 −22.5
4:00 −15.7	7:57 −18.5	7:10 −23.3	9:08 −22.5	11:56 −22.5
6:03 −14.2	8:56 −17.4	8:20 −22.7	9:58 −22.5	1:05 −22.7
7:04 −13.4	10:00 −16.5	9:27 −21.6	11:01 −22.1	2:02 −22.4
8:26 −12.2	11:10 −15.9	10:07 −21.0	12:06 −21.9	3:00 −22.3
9:08 −12.1	12:10 −16.4	11:04 −19.9	2:08 −21.3	3:56 −22.1
10:07 −12.0	2:00 −18.3	12:12 −19.1	4:30 −21.4	4:56 −21.8
11:06 −12.7	3:56 −20.3	12:58 −19.0	6:14 −22.0	6:00 −21.6
12:01 −13.1	5:56 −21.1	2:22 −19.5	8:10 −22.7	6:43 −21.4
1:06 −14.3	7:05 −19.6	3:20 −20.2	9:18 −22.6	8:08 −21.4
2:20 −15.8	8:09 −18.7	4:11 −20.8	10:02 −22.4	9:37 −22.2

TABLE IV—*Continued*

P.M. November 5	P.M. November 8	A.M. November 11	P.M. November 13	P.M. November 16
10:56 −22.3	12:57 −23.1	9:15 −22.5	9:03 −26.8	2:24 −28.4
12:56 −23.0	2:04 −23.5	10:06 −22.7	10:00 −26.1	3:09 −28.9
2:10 −22.7	3:06 −23.8	11:04 −23.2	11:00 −25.6	3:58 −29.4
4:08 −22.5	4:10 −23.5	12:12 −23.5	12:00 −25.7	5:01 −29.9
6:07 −21.8	5:01 −23.2	12:56 −24.2	2:00 −27.1	6:16 −30.7
7:03 −21.8	6:02 −22.6	1:48 −25.0	4:08 −28.8	7:52 −30.9
7:54 −21.8	6:48 −22.0	3:01 −26.0	6:29 −29.1	9:05 −30.4
8:57 −21.8	7:55 −21.4	4:10 −26.6	8:00 −28.4	10:09 −29.7
9:59 −22.2	9:02 −21.2	5:02 −26.5	9:06 −27.5	10:58 −29.2
11:00 −22.6	10:03 −21.2	5:48 −26.3	10:02 −26.9	12:12 −28.6
11:56 −22.9	11:10 −21.7	6:46 −25.5	11:02 −26.6	1:59 −28.5
1:10 −23.4	12:14 −22.6	8:00 −24.6	11:59 −26.0	4:30 −29.8
2:03 −23.4	2:00 −23.9	9:02 −23.7	12:58 −26.3	7:09 −31.0
2:58 −22.8	4:04 −24.2	10:04 −22.9	1:54 −26.9	
3:58 −22.6	6:04 −23.2	11:00 −23.0	3:00 −28.2	C = +4.54
4:57 −22.0	6:58 −22.5	12:24 −23.4	4:00 −28.9	8:06 −31.2
5:58 −21.9	8:04 −21.8	1:58 −24.9	4:56 −29.3	9:04 −31.1
6:38 −21.3	9:04 −21.5	4:01 −26.4	6:04 −29.6	10:05 −30.8
7:50 −21.3	10:05 −21.6	6:20 −26.0	6:42 −29.8	11:06 −30.0
9:00 −21.3	11:25 −22.4	7:14 −25.4	8:04 −29.0	12:04 −29.4
10:02 −21.7	1:07 −23.7	8:06 −24.8	9:03 −28.2	1:00 −29.2
11:00 −22.0	2:22 −24.3	9:08 −24.1	10:12 −27.3	2:04 −28.9
12:08 −22.6	3:33 −24.5	10:06 −23.6	11:06 −26.9	3:07 −29.6
1:03 −22.9	4:28 −24.5	11:10 −23.7	11:57 −26.6	3:56 −30.0
2:03 −22.9	5:18 −24.1	12:16 −24.0	2:02 −27.5	4:57 −30.8
4:06 −22.5	6:06 −23.6	12:58 −24.6	4:02 −29.0	5:46 −31.8
6:03 −21.6	8:16 −21.8	2:03 −25.6	5:59 −30.0	7:02 −32.5
7:04 −21.5	9:11 −21.4	3:01 −26.5	7:49 −29.8	8:00 −32.6
8:00 −21.1	10:10 −21.4	3:57 −27.3	8:58 −29.0	9:08 −32.6
9:05 −21.1	11:13 −21.5	4:57 −27.5	10:10 −28.5	10:02 −32.5
10:02 −21.2	12:12 −22.2	5:52 −27.3	11:00 −27.8	11:00 −31.9
10:57 −21.4	1:56 −23.6	6:58 −26.8	11:55 −27.2	12:04 −31.3
11:57 −22.0	3:57 −23.9	7:59 −25.9	1:03 −27.4	2:00 −30.9
12:59 −22.4	5:55 −22.9	9:03 −25.2	2:08 −28.0	4:02 −31.2
2:12 −22.8	8:12 −21.2	9:59 −24.3	3:08 −28.5	6:03 −32.7
3:04 −22.5	9:24 −21.2	11:00 −24.2	4:04 −29.5	7:20 −33.0
4:08 −21.9	10:44 −21.4	12:08 −24.2	5:08 −30:0	8:14 −33.4
5:02 −21.7	12:14 −22.5	2:18 −26.3	5:49 −30.5	9:12 −33.3
6:01 −21.3	1:01 −23.0	4:09 −27.6	6:42 −30.5	10:04 −33.0
6:45 −20.8	2:00 −23.6	6:02 −27.7	8:09 −30.5	11:02 −32.6
7:42 −20.2	3:00 −24.3	7:22 −27.1	9:06 −29.9	11:56 −31.7
9:04 −20.3	4:06 −24.5	8:18 −26.3	10:01 −29.2	1:03 −31.3
10:03 −20.3	5:08 −24.1	9:16 −25.4	10:58 −28.6	2:00 −30.9
11:05 −20.7	5:56 −23.7	10:04 −24.9	12:10 −28.1	2:56 −30.8
12:04 −21.7	6:48 −22.5	11:00 −24.4	1:58 −28.3	3:55 −30.9
2:36 −23.0	8:54 −21.3	11:58 −24.6	4:11 −30.0	4:56 −31.0
4:11 −23.0	9:59 −20.9	12:55 −25.2	6:06 −30.8	5:46 −31.6
5:59 −22.0	11:03 −21.0	1:58 −26.0	7:04 −31.0	6:40 −32.0
7:09 −21.5	12:04 −21.4	3:06 −27.1	8:02 −31.0	8:02 −32.7
8:04 −21.4	2:01 −23.0	4:02 −28.0	9:02 −30.5	9:14 −33.0
9:00 −21.2	4:05 −24.3	5:07 −28.6	10:04 −29.7	10:00 −33.0
10:02 −21.4	6:03 −23.6	5:50 −28.9	11:01 −28.9	11:02 −32.9
11:00 −21.6	7:10 −22.8	6:42 −28.4	12:08 −28.3	12:02 −32.3
11:56 −22.1	8:20 −22.3	7:54 −27.7	1:10 −27.9	2:01 −31.7

TABLE IV—*Continued*

A.M. November 19	A.M. November 21	A.M. November 23	P.M. November 25	P.M. November 27
4:05 −32.0	4:03 −32.3	7:00 −30.8	12:13 −31.7	2:01 −34.4
6:06 −32.2	5:54 −31.7	8:00 −30.2	12:58 −32.7	3:09 −35.8
7:08 −33.0	7:08 −31.2	9:03 −30.5	1:58 −33.4	4:09 −36.7
8:00 −33.5	8:01 −31.6	10:02 −30.6	3:02 −34.4	5:03 −36.9
9:12 −33.6	9:00 −31.8	11:00 −31.1	4:02 −34.8	6:10 −36.7
10:02 −33.3	9:59 −32.3	12:00 −32.2	5:00 −34.6	7:22 −36.2
11:00 −33.0	11:02 −32.5	1:05 −32.6	5:48 −34.1	8:09 −35.5
12:02 −32.6	11:57 −32.8	2:12 −33.2	6:47 −33.6	9:20 −34.7
1:16 −32.5	1:00 −33.1	3:01 −33.2	8:00 −32.4	10:09 −33.8
1:52 −32.3	2:00 −32.7	4:00 −33.1	9:00 −31.6	11:00 −33.3
C = −1.25	2:56 −32.5	4:55 −32.4	9:57 −31.2	12:00 −33.3
	4:01 −32.0	6:02 −31.5	11:00 −31.3	1:54 −34.4
2:58 −32.3	4:55 −31.6	7:55 −30.2	12:00 −32.0	3:42 −36.1
4:04 −31.6	5:56 −31.6	8:59 −30.1	2:02 −34.0	5:28 −37.2
5:04 −31.2	6:46 −31.3	10:01 −30.1	3:57 −35.2	6:29 −37.1
5:42 −32.0	7:58 −31.3	1:07 −32.7	5:48 −35.2	8:11 −35.9
6:57 −32.0	9:10 −31.5	2:59 −33.3	7:09 −34.2	8:58 −35.1
8:03 −32.4	10:07 −32.3	4:58 −32.7	8:10 −33.1	9:58 −34.3
9:12 −33.3	11:06 −32.7	7:03 −31.0	9:10 −32.2	11:00 −33.7
10:04 −33.1	12:05 −33.2	8:10 −29.9	10:08 −31.7	12:10 −33.2
10:58 −33.6	2:25 −32.4	9:12 −29.7	11:03 −31.7	1:00 −33.4
12:06 −33.3	4:00 −32.5	10:00 −29.9	12:12 −32.4	2:01 −34.3
2:00 −32.6	6:00 −31.4	11:08 −30.9	12:56 −33.2	3:10 −35.5
4:03 −32.2	7:06 −30.9	11:58 −31.8	1:58 −34.2	4:00 −36.3
5:55 −32.1	8:00 −31.0	1:04 −32.9	3:02 −35.3	4:58 −37.0
7:04 −32.4	9:00 −31.3	2:00 −33.7	4:00 −36.0	5:54 −37.5
8:00 −32.6	10:07 −31.7	3:12 −34.1	4:57 −36.6	6:49 −37.4
9:16 −33.3	11:00 −32.1	4:07 −33.9	5:51 −36.4	8:00 −37.0
10:10 −33.3	11:54 −32.8	5:01 −33.5	6:44 −35.8	8:39 −36.4
11:00 −33.4	1:00 −33.4	5:55 −32.8	7:54 −34.5	10:10 −35.1
12:02 −33.6	2:04 −33.2	6:44 −32.1	9:00 −34.1	11:52 −34.1
12:57 −33.4	3:11 −33.3	8:04 −30.8	10:04 −33.0	3:07 −35.4
1:55 −32.9	4:06 −32.7	9:02 −30.5	11:08 −32.7	5:09 −36.9
3:00 −32.4	5:01 −32.1	10:05 −30.6	12:27 −33.4	6:58 −37.2
3:58 −32.0	5:48 −31.8	10:56 −30.9	1:58 −34.6	8:14 −36.5
4:56 −31.8	6:40 −31.2	12:00 −31.8	4:17 −36.6	9:22 −35.6
5:49 −31.6	7:54 −30.8	2:02 −33.6	5:57 −36.6	10:41 −34.7
6:46 −31.9	9:09 −31.0	4:08 −34.4	7:07 −35.6	11:56 −33.7
7:56 −32.0	9:58 −31.4	6:00 −32.9	8:14 −34.8	1:15 −33.8
9:00 −32.5	11:10 −32.1	7:11 −32.0	9:10 −33.7	2:10 −34.3
10:06 −33.0	12:12 −32.9	8:16 −31.1	9:58 −32.9	
10:59 −33.3	2:01 −33.3	9:06 −30.6	10:58 −32.8	
12:04 −33.3	4:01 −33.0	9:59 −30.3	12:01 −32.7	
1:57 −33.1	6:02 −31.4	10:57 −30.7	12:42 −33.2	

RYERSON PHYSICAL LABORATORY
February 15, 1914

THE VARIATION WITH TEMPERATURE OF THE ELECTRIC FURNACE SPECTRUM OF TITANIUM[1]

By ARTHUR S. KING

Certain features of the spectrum of titanium, when this metal is vaporized in the electric furnace, have been treated in previous papers by the writer. In the first[2] of these it was shown that a rich titanium spectrum may be produced by the furnace, and its leading characteristics were compared with those of the arc spectrum. The second paper[3] dealt with the pressure-shifts of titanium lines in the furnace; while a more recent one[4] takes up the conditions for the production of enhanced lines in this source, the discussion leading to a consideration of the "tube-arc," the spectrum of which is very different from that of the furnace when operated in the regular way.

In the present paper, the treatment of the titanium spectrum will follow the general plan of a recent paper[5] on the spectrum of iron. The purpose is to examine the spectra given by three stages of furnace temperatures in the range from 2000° C. to above 2600° C. The data thus obtained show the approximate temperature at which a line appears and the rate of growth in intensity as the temperature rises. The strength of the line in the arc spectrum is also noted and a classification of the lines is obtained similar to that given for the iron spectrum. The range of wave-length studied is approximately that of the visible spectrum, from λ 3888 to λ 7364.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 76.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 60; *Astrophysical Journal*, **35**, 183, 1912.

[4] *Contributions from the Mount Wilson Solar Observatory*, No. 65; *Astrophysical Journal*, **37**, 119, 1913.

[5] *Contributions from the Mount Wilson Solar Observatory*, No. 66; *Astrophysical Journal*, **37**, 239, 1913.

APPARATUS AND METHODS

The tube resistance furnace and the two grating spectographs used in this work have been described in previous papers, the experimental method being very similar to that employed for the iron spectrum. The metal, "cast titanium," supplied by Eimer & Amend, was placed in the tube in a finely powdered condition. On account of the high melting-point of titanium (in the neighborhood of 1900° C.), a temperature close to 2100° C. as measured by a Wanner pyrometer was required before any considerable number of lines appeared. As nearly as I have been able to determine, even the lowest temperature lines do not appear below 2000° C. At about 2300° C. many lines have developed which are absent at 2100°. At 2300° to 2400° almost all lines have appeared which show in the arc spectrum, the absent ones being weak arc lines and the enhanced lines. The change from 2300° to 2600° has as its most interesting feature the differences in the rate of development of the lines which are present at the lower temperature. The highest temperatures employed may have been considerably above 2600° in the hottest part of the tube, but the relative intensities of the titanium lines were not greatly different from the condition at 2500°, except that, as was shown in a former paper,[1] at about 2600° we reach the stage when enhanced lines can be made to appear faintly in the furnace spectrum. The strong vaporization of carbon at these higher temperatures is disturbing, not only on account of the band spectrum in certain regions, but by reason of the strong continuous spectrum emitted, probably at least in part from the reflection of light from the incandescent wall of the tube by the vapor particles. This vaporization of the carbon causes the gain in temperature to be slow in proportion to the electrical energy expended, and with the size of tubes thus far used, superheating much above 2600° C. has not yielded photographs satisfactory for comparison with those taken at lower temperatures.

A set of photographs for the range from λ 3880 to λ 5700 was taken three years ago, the first order of the vertical plane-grating spectrograph being used with objective of 30 ft. (9.1 m) focal

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 65; *Astrophysical Journal*, **37**, 119, 1913.

length, the scale being about 2.05 A per mm. The requirements as to scale for this spectrum in the blue and violet are somewhat exacting, however, on account of the numerous close lines, and a decided gain was obtained in a set of plates taken during the past year in which the bright second order of a new grating was used for the spectrum to the violet of λ 4600, the scale being approximately 0.9 A per mm. Cramer "Crown" plates were used for this region. To supplement the former set, the first order of the same grating was employed for lines to the red of λ 4600, with Seed "Gilt-Edge 27" plates bathed with pinacyanol, pinaverdol, and homocol according to the formula of Wallace. A fairly uniform intensity of the spectrum was thus obtained from λ 4600 to about λ 6800, from which point the decreasing sensitiveness of the plates made furnace photographs with the long-focus instrument very difficult. For the few lines beyond λ 6800, I have relied upon bathed films used with a concave grating of 1 meter radius, the brightness of whose spectra makes it possible to photograph the furnace radiation as far into the red as titanium lines have been measured in the arc spectrum.

A number of photographs were made with this concave grating, covering with one exposure the whole visible spectrum, frequently simultaneously with exposures made with the large-scale instrument. While the estimates of intensities were based almost entirely on plates taken with the plane grating, the films taken with the concave were useful as supplementary material, especially for the low and medium temperatures, and showed the general variation of the spectrum with wave-length for the several temperatures and for the arc. They were especially useful by reason of the strong spectrum which could be obtained at low temperature, the large spectrograph giving the spectrum very faint for this condition; so that if a line did not appear on the film taken with the concave grating, it was reasonably certain that the temperature employed would not produce such a line.

The method of estimating line intensities was discussed in some detail in connection with the iron spectrum. The same system was used for the titanium lines. The effort has been to obtain correct relative intensities among the lines for each temperature,

a line distinctly outlined on the negative being graded "1," a fainter appearance being indicated by "trace." The difficult gap between reversed and unreversed lines could usually be bridged on a given plate by means of partially reversed lines, the relation of whose intensity both to unreversed and to completely reversed lines was fairly clear. A considerable degree of consistency can thus be attained for the intensity scale of lines at a given temperature. When different temperatures are compared, however, each temperature condition involves a certain adjustment of emission and absorption between the vapor at the center and that toward the ends of the tube, the effect being to give a line less density in proportion to its width at the higher temperatures. While this affects the photometric accuracy attainable in comparing lines for different temperatures, the differences on which the classification of lines is based are so decided that this grouping, which shows the stage for the initial appearance of a line and its rate of growth relatively to other lines, may be considered as governed by the actions attendant on temperature change.

The detection of possible blends with impurity lines has been assisted by the fact that furnace spectra were available for several of the elements most likely to be found with titanium. By this means it could be seen whether a line of one of these elements, even if weak in its own arc spectrum, was likely to occur at a given furnace temperature. The use of tubes of specially purified Acheson graphite, and the large scale employed in the blue and violet where the lines are most numerous, aided in the treatment of impurity lines. Vanadium was the most disturbing element in this regard, the stronger lines being given by the graphite tube as well as by impurities in the titanium. In a few cases, vanadium lines which might be present agreed so closely in position with titanium lines that it was necessary to ascertain the probable intensity of the vanadium line from the regular vanadium furnace spectrum and deduct this from the blend appearing on the titanium plate. Such cases are noted in the "Remarks" column of Table I.

EXPLANATION OF THE TABLE

Wave-lengths.—It was desirable in this work to use a table of wave-lengths covering the whole visible spectrum and including

the fainter lines visible in a strong arc spectrum of titanium. These requirements were filled satisfactorily by the tables of Exner and Haschek,[1] supplemented for the extreme red by the measurements of Fiebig[2] on the international system. The wave-lengths given by Rowland for the solar spectrum are not as complete for titanium as they are for iron, owing to the general faintness of the titanium spectrum in the sun. Many such lines are not identified by Rowland as titanium. However, for convenience in comparing with the solar spectrum, the solar wave-length most closely agreeing with the titanium line in the arc is entered in the second column, whether given by Rowland as titanium or not. In nearly all cases there is little question that the solar line is due at least in part to titanium. The wave-lengths of Hasselberg[3] are used in a few cases when close doublets were not resolved by Exner and Haschek. As far as the measurements of Hasselberg extend (to λ 5900), they agree, except in rare cases, with those of Exner and Haschek within 0.05 A.

Arc intensities.—These have been estimated by the writer from arc spectra taken on the same plates with some of the best furnace spectra. A carbon arc containing titanium in the lower (positive) terminal was used, with currents of 6 to 8 amperes, the central portion of the arc being projected on the slit. Usually several arc spectra with varying exposures were photographed on the same plate. It was necessary to select a strong arc spectrum for comparison with the furnace, since many titanium lines which are faint in the arc were found to show with considerable strength in the furnace. Many lines in the arc spectrum are somewhat diffuse, shading off from the center without well-defined edges. These nebulous lines are indicated by *n* after the intensity. There is some difficulty in rating their intensities on the same scale as is used for the sharper lines. The letters *R* and *r*, both for arc and for furnace lines, indicate complete and partial self-reversal, respectively. These symbols point out the lines most subject to reversal, but the degree of reversal depends upon the supply of vapor and whether the arc is quiet or explosive in its action.

[1] *Spektren der Elemente bei normalem Druck*, Leipzig, 1911.

[2] *Zeitschr. f. wiss. Phot.*, **8**, 73, 1910.

[3] *Astrophysical Journal*, **4**, 116, 212, 1896.

Furnace intensities.—The furnace spectrum was photographed at three temperatures, the centigrade values of which were about 2100°, 2300°–2400°, and 2600°–2700°. These are designated as "low," "medium," and "high," respectively. It will be noted that in Table I the intensities scale downward in general, for the three furnace temperatures. This results from taking the spectra just as they appear on the plates and using as the unit of intensity for each a line distinctly outlined on the plate. With the large-scale spectrograph, exposures of an hour or more at 2100° did not suffice to give a general intensity of the spectrum such as could be obtained with 2600° in two to three minutes. Even the most pronounced low-temperature lines did not come to the same absolute strength as on the high-temperature photographs. This does not interfere with the classification, however, since the important point is the relative change of different lines with increase of temperature.

Classification.—The class to which a line belongs is given in the seventh column. The method of forming classes, which was described in detail for the iron spectrum, has been adhered to as far as possible and may be given briefly here. *Class I* lines are relatively strong at low temperature and strengthen slowly at higher temperatures. For the iron spectrum this class was divided into I A and I B according to the strength of the line in the arc spectrum. A few Class I A lines occur with titanium, being faint in the arc, but it has been found convenient to use "A" with other classes which show this peculiarity of relative weakness in the arc as compared with the furnace, especially for Class III; so that lines corresponding to Class I B for iron, which are strong in the arc as well as in the furnace, will be given here as belonging to Class I. *Class II* lines appear at the lowest temperature but strengthen rather rapidly as the tube becomes hotter, and are strong in the arc, except in the case of a few lines placed in Class II A. The lines of *Class III* are absent or faint at low temperature, appear at medium temperature, and are usually considerably stronger at high temperature. Many titanium lines of this kind are relatively weak in the arc, so that for this spectrum Class III A becomes important. *Class IV*

TABLE I

TEMPERATURE CLASSIFICATION OF TITANIUM LINES

λ (EXNER AND HASCHEK)	NEAREST SOLAR LINE (ROWLAND)	ARC	FURNACE			CLASS	REMARKS
			High Temp.	Medium Temp.	Low Temp.		
3888.16	.179	4 *n*	2	Tr.	.....	IV	
3890.12	.069	6	6	6	Tr.	III	
3895.42	.377	30 *n*	8	2	1	III	
3897.45	.482	1	1	.....	.....	IV	
3897.72	.785	1	1	.....	.....	IV	
3898.64	.645	8	6	6	1	III	
3900.72	.681	50	.....	.....	.....	V E	
3901.14	.114	12	10*r*	6	2	II	
3904.99	.926	40*n*	25*R*	8	3	II	
3911.36	.316	8*n*	4	1	.....	III	
3912.75	.732	2	1	.....	.....	IV	
3913.68	.609	40	.....	.....	.....	V E	
3914.50	.477	35	18*R*	7	4	II	
3914.86	.880	5	5	5	.....	III	
3916.00	5.951	3	6	4	.....	III A	
3916.21	.207	3	Tr.	.....	.....	IV	
3919.95	.956	5	5	2	.....	III	
3921.61	.563	30	15*R*	8	3	II	
3924.71	.673	50	30*R*	12	5	II	
3926.45	.465	10	4	Tr.	.....	IV	
3930.04	.022	40	20*R*	10	6	II	
3934.35	.508	9	8	6	Tr.	III	
3938.13	.116	2*n*	1	.....	.....	IV	
3947.98	.918	40	30*R*	12	6	II	
3948.87	.818	60	50*R*	20*r*	8	II	
3956.50	.476	60	40*R*	18	10	II	
3958.39	.355	80	60*R*	25*r*	12	II	
3963.05	2.995	35	20*R*	12	6	II	
3964.48	.416	35	20*R*	12	6	II	
3980.98	.963	1	1	.....	.....	IV	
3981.95	.917	70*r*	50*R*	25*r*	10	II	
3982.63	.630	30	15*R*	10	6	II	
3984.46	.479	3	3	1	.....	III	
3985.40	.385	3	1	Tr.	.....	III	
3985.70	.745	3	2	Tr.	.....	III	
3989.94	.912	80*r*	60*R*	30*r*	10	II	
3992.55	.538	2*n*	.....	.....	.....	V	
3993.94	.978	1	Tr.	.....	.....	IV	
3994.84	.828	4*n*	4	1	.....	III	
3998.80	.790	100*R*	70*R*	40*R*	12	II	
3999.47	.495	7*n*	3	1	.....	III	
4002.62	.652	9*n*	5	2	.....	III	
4003.95	.912	10*n*	5	2	.....	III	
4006.10	.114	6*n*	4	1	.....	III	
4007.31	.310	3*n*	2	Tr.	.....	IV	
4008.21	.215	9*n*	5	2	.....	III	
4009.12	.079	35	25*R*	12	8	II	
4009.82	.807	15	12*r*	8	3	II	
4012.55	.541	10	.....	.....	.....	V E	
4012.95	.941	3	1	Tr.	.....	III	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4013.72	.729	12*n*	6	3	.....	III	
4015.51	.532	12*n*	6	3	.....	III	
4016.40	.434	6	3	1	.....	III	
4017.10	.114	3	1	Tr.	.....	III	
4017.90	.925	15*n*	7	4	.....	III	
4022.00	.018	25*n*	8	4	.....	III	
4024.76	.726	35	25*R*	15	8	II	
4025.30	.286	4	.....	.....	.....	V E	
4026.71	.691	25*n*	8	4	.....	III	
4027.64	.623	4	Tr.	.....	.....	IV	
4028.48	.497	5	.....	.....	.....	V E	
4030.66	.646	25*n*	10	4	.....	III	
4031.90	.042	3*n*	3	1	.....	III	
4032.76	.789	3*n*	.....	.....	.....	V	
4034.05	.052	6	4	1	.....	III	
4035.04	.018	5	2	Tr.	.....	III	
4035.96	.976	10	6	2	.....	III	
4040.45	.464	4*n*	4	1	.....	III	
4043.91	.956	2	1	.....	.....	IV	
4049.51	.482	2*n*	2	Tr.	.....	III	
4053.10	.091	2	2	Tr.	.....	III	
4053.96	.981	4	.....	.....	.....	V E	
4055.17	.189	20	10	8	Tr.	III	
4057.76	.817	5	3	Tr.	.....	III	
4058.29	.372	7	5	1	.....	IV	
4060.42	.415	20	10	10	Tr.	III	
4064.39	.361	15	9	6	.....	III	
4065.24	.239	15	9	8	Tr.	III	
4068.29	.268	3	1	.....	.....	IV	
4069.15	.115	4*n*	1	.....	.....	IV	
4071.41	.501	2	1	.....	.....	IV	
4071.67	.680	2	1	.....	.....	IV	
4074.55	.488	3	1	.....	.....	IV	λ by Hasselberg, not given by Exner and Haschek
4076.53	.516	4	8	8	.....	III A	
4077.20	.221	4	1	Tr.	.....	IV	
4078.62	.631	30	18	15	2	III	
4079.86	.863	6	3	1	.....	III	
4082.65	.589	20	12	12	Tr.	III	
4099.32	.327	8	5	2	.....	III	
4112.87	.869	20	20*r*	15	5	II	
4120.16	.202	2	1	Tr.	.....	III	
4121.79	.805	4	6	4	.....	III	
4122.30	.306	10	3	1	.....	III	
4123.43	.430	5*n*	1	.....	.....	IV	
4123.70	.713	10	5?	2?	.....	III?	Coincides with *V*. Probable intensity of *V* line subtracted
4127.67	.689	15	4	2	.....	III	
4129.30	.337	4	2	Tr.	.....	III	
4131.42	.419	4	2	Tr.	.....	III	
4137.46	.428	10*n*	5	3	.....	III	
4140.03	.089	2	1	.....	.....	IV	
4142.68	.629	2	1	.....	.....	IV	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4143.22	.200	7*n*	4	1	.....	III	
4143.41	.430	3	2	Tr.	.....	III	
4150.73	.706	3	2	Tr.	.....	III	
4151.12	.129	10	5	2	.....	III	
4155.00	4.976	2	1	.....	.....	IV	
4159.80	.805	9	5?	2?	.....	III?	Slightly affected
4161.70	.682	2	.....	.....	.....	V E	in furnace by
4163.83	.818	8	.....	.....	.....	V E	*V* blend
4164.31	.313	4	3	1	.....	III	
4166.49	.511	6	4	2	.....	III	
4169.51	.499	7	5	2	.....	III	
4171.20	.213	8	5	2	.....	III	
4172.10	.066	5	.....	.....	.....	V E	
4173.71	.710	3	.....	.....	.....	V E	
4174.27	.240	2	.....	.....	.....	V E	
4174.65	.647	3	2	Tr.	.....	III	
4183.46	.480	4	2	Tr.	.....	III	
4186.29	.280	25	10	8	Tr.	III	
4188.84	.894	5	3	Tr.	.....	III	
4200.90	.946	6	4	1	.....	III	
4203.59	.620	8	6	1	.....	IV	
4211.88	.899	4	4	3	.....	III	
4224.97	5.020	5	2	.....	.....	IV	
4227.81	.822	5	3	Tr.	.....	III	
4238.05	.050	7	4	1	.....	III	
4245.65	.671	2	2	Tr.	.....	III	
4249.28	.272	5*n*	4	1	.....	III	
4251.74	.783	3	4	1	.....	III	
4251.90	.905	2*n*	2	Tr.	.....	III	
4256.19	.177	8*n*	7	2	.....	III	
4258.70	.774	4*n*	5	1	.....	IV	
4260.91	.888	2	2	.....	.....	IV	
4261.79	.748	5*n*	6	2	.....	III	
4263.31	.290	15	12	5	Tr.	III	
4265.44	.418	3*n*	3	Tr.	.....	III	
4265.88	.832	4	5	1	.....	IV	
4266.39	.374	3*n*	4	Tr.	.....	IV	
4270.30	.329	7*n*	7	1	.....	IV	
4272.58	.590	8	12	6	1	III A	
4273.46	.482	2	2	.....	.....	IV	
4274.75	.746	15	15	9	Tr.	III	
4276.60	.587	8	10	3	.....	III	
4276.80	.836	2	3	Tr.	.....	III	
4278.39	.390	7	6	1	.....	IV	
4278.95	9.009	3*n*	4	1	.....	III	
4280.25	.194	2*n*	3	Tr.	.....	III	
4280.49	.494	1*n*	Tr.	.....	.....	IV	
4281.54	.530	10	10	8	2	III	
4282.87	.860	12	10	4	.....	III	
4285.15	.164	8	8	3	.....	III	
4286.19	.168	25	25*r*	20	6	II	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4287.59	.566	22	25*r*	20	5	II	
4288.04	.038	2	.....	.....	.....	V E	
4288.30	.310	3	12	5	.....	III A	
4289.26	.237	25	25*r*	22	8	II	
4290.09	.080	3	3	Tr.	.....	III	
4290.40	.377	8	Tr.	.....	.....	V E	
4291.19	.174	22	25*r*	20	6	II	
4291.34	.375	5*n*	10	1	.....	IV	Shaded toward red in furnace and arc. May be double
4292.84	.827	1	4	1	.....	III A	
4294.29	.301	8	.....	.....	.....	V E	
4295.93	.914	22	25*r*	20	6	II	
4298.89	.828	40	40*R*	25	10	II	
4299.40	.410	15	20	5	1	III	
4299.81	.803	15	20	12	2	III	
4300.20	.211	12	Tr.	.....	.....	V E	
4300.73	.732	50	50*R*	30	15	II	
4301.24	.262	50	50*R*	30	15	II	
4302.06	.085	5	.....	.....	.....	V E	
4303.13	.072	1*n*	3	1	.....	III A	
4305.65	.614	2	4	1	.....	III A	
4306.09	.078	60	60*R*	40	20	II	
4307.10	.017	1	5	2	.....	III A	
4308.05	.081	12	Tr.	.....	.....	V E	
4308.65	.601	2	6	2	.....	III A	
4309.23	.198	1	1	.....	.....	IV	
4310.55	.540	1	4	1	.....	III A	
4311.81	.880	2	2	.....	.....	IV	
4313.04	.034	7	.....	.....	.....	V E	
4314.52	.479	5	10	6	.....	III A	
4314.96	.964	25	25	20	6	II	
4315.12	.138	5	.....	.....	.....	V E	
4318.85	.817	10*n*	8?	3?	.....	III	Slightly affected by blend with *V* and *Ca*
4321.15	.119	1	.....	.....	.....	V E	
4321.89	.813	8*n*	6	2	.....	III	
4323.63	.670	1	5	2	.....	III A	
4325.36	.306	9*n*	7	3	.....	III	
4326.54	.520	9	10	8	2	II	
4327.15	.082	2	7	3	.....	III A	
4330.91	.866	1	.....	.....	.....	V E	
4335.03	4.965	2	8	4	Tr.	III A	
4338.09	.084	10	Tr.	.....	.....	V E	
4338.65	.616	1	1?	.....	.....	IV?	Diffuse in furnace. May belong to carbon band
4340.19	.192	1	Tr.?	.....	.....	IV?	
4341.50	.530	2	.....	.....	.....	V E	
4343.96	4.015	1	1	.....	.....	IV	
4344.44	.451	3	.....	.....	.....	V E	
4346.28	.278	5	5	1	.....	IV	
4346.75	.725	1	1	.....	.....	IV	
4354.25	.228	3	3	1	.....	III	
4355.48	.509	1	2	.....	.....	IV A	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4360.68.....	.644	4	3?	1?	.....	III?	Blend with *V*.
4361.30.....	.219	1	1	.....	.....	IV	Probable intensity of *V* line subtracted
4367.89.....	.882	1	.....	.....	.....	V E	
4369.10.....	.052	2	2	.....	.....	IV	
4369.87.....	.873	5*n*	4	Tr.	.....	IV	
4372.57.....	.498	3	4	Tr.	.....	IV	
4375.60.....	.643	1	1	.....	.....	IV	
4388.21.....	.260	3	4	1	.....	III	
4388.65.....	.571	1	1	.....	.....	IV	
4394.11.....	.093	8	8	2	.....	III	
4394.27.....	.225	2	.....	.....	.....	V E	
4395.19.....	.201	25	Tr.	.....	.....	V E	
4396.00.....	.008	1	.....	.....	.....	V E	
4399.94.....	.935	6	.....	.....	.....	V E	
4404.42.....	.433	10	8	2	.....	III	λ's by Hasselberg, given by Exner and Haschek as 4404.47
4404.57.....	.563	5	10	4	.....	III A	
4405.04.....	.082	5	6	2	.....	III	
4405.83.....	.896	2	9	3	.....	III A	
4412.60.....	.581	1	6	2	.....	III A	
4416.70.....	.636	4	3?	1?	.....	III?	Blend with *V*.
4417.47.....	.450	15	10	5	Tr.	III	Probable intensity of *V* line subtracted
4417.86.....	.884	8	.....	.....	.....	V E	
4418.52.....	.499	1	.....	.....	.....	V E	
4421.67.....	.616	1	1	.....	.....	IV	
4421.98.....	.928	6	6	2	.....	III	Not enhanced, as given by Lockyer. Enhanced line is λ 4422.12
4423.01.....	2.985	10	12	7	2	II	
4424.56.....	.531	2	3	Tr.	.....	III	
4426.01.....	5.931	3	10	2	.....	III A	
4426.20.....	.201	10	6?	2?	.....	II?	Blend with *V*.
4427.28.....	.266	40	25	15	2	III	Probable intensity of *V* line subtracted
4430.21.....	.221	3	2	Tr.	.....	III	
4430.52.....	.524	7	10	4	.....	III A	
4431.45.....	.453	4	4	1	.....	III	
4432.76.....	.736	2	2	.....	.....	IV	
4433.76.....	.742	3	2	Tr.	.....	III	
4434.16.....	.168	15	20	8	Tr.	III A	
4434.54.....	.504	1	1	.....	.....	IV	λ by Hasselberg. Not given by Exner and Haschek
4436.79.....	.750	4	5	2	.....	III	
4438.39.....	.359	2	2?	.....	.....	IV	May be partly *Sr*
4440.53.....	.515	10	10	3	Tr.	III	
4441.45.....	.433	4	5	1	.....	IV	
4444.00.....	3.976	25	1	.....	.....	V E	
4444.74.....	.728	1	.....	.....	.....	V E	
4449.35.....	.313	30	15	12	2	III	
4450.20.....	.267	1	1	.....	.....	IV	
4450.70.....	.654	4	.....	.....	.....	V E	
4451.13.....	.087	25	15	10	2	III	
4453.52.....	.486	30	25	18	5	II	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4453.91	.876	20	12	8	1	III	
4455.50	.485	30	25	18	5	II	
4457.61	.600	40	35	25	7	II	
4463.52	.569	8	7	2	.....	III	λ's by Hasselberg. Given by Exner and Haschek as λ 4463.62
4463.70	.698	8	7	2	.....	III	
4464.62	.617	2	.....	.....	.....	V E	
4465.97	.975	20	12	8	1	III	
4468.65	.663	25	1	.....	.....	V E	
4469.38	.316	1	.....	.....	.....	V	
4471.04	.017	2	1	.....	.....	IV	
4471.43	.408	20	12	8	1	III	
4475.02	.026	8	10	5	Tr.	III	
4475.68	.633	1	1	.....	.....	IV	
4479.88	.879	9	9	3	.....	III	
4480.78	.752	5	7	2	.....	III A	
4481.46	.438	30	18	12	2	III	
4482.87	.904	10	10	5	.....	III	
4485.24	.244	1	2	.....	.....	IV A	
4488.45	.493	2	.....	.....	.....	V E	
4489.25	.262	20	15	8	1	III	
4492.73	.700	3	4	1	.....	III	
4495.18	.182	4	3	1	.....	III	
4496.35	.318	20	15	5	.....	III	
4496.44	.409	2	15	10	2	III A	Measured by writer. In arc appears as satellite of λ 4496.35
4497.91	.842	3	4	1	.....	III	
4501.42	.445	25	1	.....	.....	V E	
4503.94	.926	4*n*	5	1	.....	IV	
4505.89	.959	1	1	.....	.....	IV	
4506.50	.497	2*n*	3	.....	.....	IV	
4508.20	.177	2	2	.....	.....	IV	
4508.44	.455	1	1	.....	.....	IV	
4511.31	.345	3	2	.....	.....	IV	
4512.90	.906	40	40*r*	20	8	II	
4513.85	.886	1	3	.....	.....	IV A	
4515.74	.763	1	2	.....	.....	IV A	
4518.19	.198	50	50*r*	20	12	II	
4518.83	.866	8	10	4	.....	III	
4522.98	.974	40	40*r*	20	12	II	
4526.52	.579	1	4	1	.....	III A	
4527.47	.490	35	35*r*	18	10	II	
4529.64	.656	1	.....	.....	.....	V E	
4532.30	.306	1	1	.....	.....	IV	
4533.40	.419	80	80*R*	45	35	II	
4534.14	.139	20	Tr.	.....	.....	V E	
4534.95	.953	60	60*R*	30	25	II	
4535.71	.741	50	50*R*	25	20	II	
4536.12	.094	40	40*r*	20	15	II	λ's by Hasselberg. Given by Exner and Haschek as λ 4536.16
4536.25	.222	40	40*r*	18	12	II	
4537.40	.389	2	2	.....	.....	IV	
4539.26	.263	3	2	.....	.....	IV	

TABLE I—*Continued*

Å (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4540.66	.672	1	10	5	.....	III A	May be slightly affected by *Cr* λ 4540.64
4541.05	.043	1	3	1	.....	III A	
4544.88	.864	30	30*r*	15	8	II	
4547.51	.587	1	Tr.	.....	.....	IV	
4548.01	.024	2	2	Tr.	.....	III	
4548.30	.301	2	2	Tr.	.....	III	
4548.93	.938	35	35*r*	18	12	II	
4549.80	.808	25	Tr.	.....	.....	V E	
4552.70	.725	35	35*r*	18	12	II	
4555.27	.264	3	3	Tr.	.....	III	
4555.70	.662	30	30*r*	15	10	II	
4558.03	.060	2	2	.....	.....	IV	
4558.30	.285	2	2	.....	.....	IV	
4560.10	.102	6	8	3	.....	III	
4562.80	.814	6	12	10	3	II A	
4563.61	.599	5	4	1	.....	III	
4563.93	.939	15	.....	.....	.....	V E	
4564.36	.352	1	3	1	.....	III A	
4571.07	.095	3*n*	3	Tr.	.....	III	
4572.15	.156	15	.....	.....	.....	V E	
4585.97	6.047	2	Tr.	.....	.....	IV	
4590.12	.126	3	.....	.....	.....	V E	
4599.40	.408	5	1	.....	.....	IV	
4609.54	.540	2	.....	.....	.....	V	
4614.45	.388	1	.....	.....	.....	V	
4617.40	.452	30	15	8	2	II	
4619.66	.607	3	*	.....	.....	IV?	
4623.25	.279	25	12	5	1	III	
4629.47	.521	15	8	3	Tr.	III	
4635.67	.736	3	*	.....	.....	IV?	
4637.36	.352	2	*	.....	.....	IV?	
4638.00	.050	8	3?	.....	.....	IV?	Furnace line may be due to *C*
4639.49	.538	18	10	3	1	III	
4639.79	.846	15	10	3	1	III	
4640.10	.119	15	10	3	1	III	
4640.55	.468	2	2?	.....	.....	IV?	Furnace line may be due to *C*
4645.36	.368	12	6	2	Tr.	III	
4650.18	.193	10	5	2	Tr.	III	
4655.84	.832	3	3?	.....	.....	IV?	Furnace line may be due to *C*
4656.20	.228	6	5	2	.....	III	
4656.63	.644	25	20	12	10	I	These lines are given very strongly by vapor near ends of furnace tube
4667.77	.766	25	18	12	10	I	
4668.55	.550	2	*	.....	.....	IV?	
4675.30	.294	10	10	3	Tr.	III	
4677.15	.096	1	*	.....	.....	IV?	
4677.68	.604	2	*	.....	.....	IV?	
4682.10	.088	30	20	15	12	I	Similar to λλ 4657 and 4668
4684.71	.702	2	*	.....	.....	IV?	
4687.10	.114	4	*	.....	.....	IV?	
4688.56	.554	3	*	.....	.....	IV?	

*Occurrence uncertain on account of strong carbon spectrum at high temperature, but *Ti* lines are weak in furnace, if present at all. Provisionally placed in Class IV.

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4691.02	0.977	3	*	.....	.....	IV?	
4691.50	.523	20	12	8	2	II	
4693.88	.852	5	10	6	2	II A	
4697.13	.101	4	*	.....	.....	IV?	
4698.97	.946	20	12	7	2	II	
4709.15	.153	1	*	.....	.....	IV?	
4710.38	.368	18	15	4	Tr.	III	
4715.48	.474	4	12	6	3	II A	
4722.79	.797	10	10	4	Tr.	III	
4723.35	.359	10	10	4	Tr.	III	
4731.35	.356	9	4	1	.....	III	
4733.57	.604	6	*	1	.....	III?	
4734.86	.847	3	*	.....	.....	IV?	
4742.32	.307	3	1	.....	.....	IV	
4742.98	.979	20	8	3	.....	III	
4747.46	.469	1	4	1	.....	III A	
4747.87	.868	3	2	1	.....	III	
4758.30	.308	25	12	3	Tr.	III	
4759.08	.107	4	9	3	Tr.	III A	
4759.43	.463	25	12	3	Tr.	III	
4764.10	.108	1	.....	.....	.....	V E	
4766.51	.621	4	2	Tr.	.....	III	
4769.98	.991	4	3	Tr.	.....	III	
4771.30	.279	3	8	2	.....	III A	
4778.43	.441	10	5	2	.....	III	
4780.17	.169	2	.....	.....	.....	V E	
4781.90	.913	6	12	4	Tr.	III A	
4792.70	.702	10	6	2	.....	III	
4796.41	.373	6	4	Tr.	.....	III	
4798.17	.169	5	2	Tr.	.....	III	May be slightly affected by *V* blend
4800.00	9.984	12	8	2	.....	III	
4805.24	.285	4	.....	.....	.....	V E	
4805.60	.606	12	9	2	.....	III	
4808.70	.733	5	3	.....	.....	IV	
4811.27	.235	4	2	.....	.....	IV	
4812.43	.427	5	4	1	.....	III	
4819.25	.205	2	1	.....	.....	IV	
4820.59	.593	20	15	8	2	II	
4825.65	.666	3	2	.....	.....	IV	
4827.76	.804	2	?	.....	.....	IV?	Blend with strong *V* line
4836.29	.313	6	4	1	.....	III	
4841.08	.074	25	20	15	12	I	
4844.16	.210	2	1	.....	.....	IV	
4848.60	.605	8	5	1	.....	IV	
4856.20	.203	20	12	3	.....	III	
4864.39	.362	4	3	1	.....	III	
4868.42	.451	18	10	3	.....	III	
4870.31	.323	20	12	4	.....	III	
4881.13	.128	3	2	.....	.....	IV	
4882.54	.518	2	1	.....	.....	IV	
4885.25	.264	20	15	8	2	II	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
4892.03	.047	1	Tr.	.....	.....	IV	λ by Hasselberg. Not given by Exner and Haschek
4893.26	.228	2	1	.....	.....	IV	
4893.64	.606	2	Tr.	.....	.....	IV	
4900.10	.095	20	15	7	1	III	
4901.15	.152	1	Tr.	.....	.....	IV	
4909.28	.283	2	6	2	.....	III A	
4913.80	.803	20	12	7	1	III	
4915.40	.414	5	4	1	.....	III	
4920.05	.047	10	8	2	.....	III	
4921.96	.963	12	9	2	.....	III	
4925.59	.594	5	5	1	.....	IV	
4926.34	.334	4	10	3	.....	III A	
4928.50	.511	12	10	2	.....	III	
4937.93	.902	4	12	3	.....	III A	
4938.47	.467	8	4	Tr.	.....	IV	
4941.76	.752	3	1	.....	.....	IV	
4948.18	.120	1	4	2	.....	III A	
4948.39	.368	3	1	.....	.....	IV	
4958.49	.431	2	5	1	.....	III A	
4964.94	.903	5	5	1	.....	III	
4968.74	.769	6	6	2	.....	III	
4973.21	.281	6	5	1	.....	III	
4975.50	.530	10	4	1	.....	III	
4976.99	7.056	1	Tr.	.....	.....	IV	
4977.95	.891	5	4	Tr.	.....	IV	
4978.39	.372	10	8	2	.....	III	
4981.93	.912	60	50*r*	30	20	II	
4989.30	.325	10	9	3	.....	III	
4991.24	.247	50	40*r*	25	18	II	
4997.27	.283	8	12	12	6	I A	
4999.68	.689	45	40*r*	25	18	II	
5001.16	.165	10	15	5	.....	III A	
5007.35	.398	40	35	20	15	II	
5009.79	.829	7	15	12	5	I A	
5013.47	.479	18	10	3	.....	III	
5014.39	.369	50	50*r*	30	25	II	
5016.29	.340	20	15	12	6	II	
5020.20	.208	25	20	15	8	II	
5023.02	.052	25	20	15	8	II	
5025.01	.027	20	18	12	7	II	
5025.75	.749	18	8	4	Tr.	III	
5036.08	.189	25	15	12	4	II	
5036.65	.645	25	15	12	4	II	
5038.59	.579	25	15	10	3	II	
5040.14	.138	22	30	20	15	I	Given strongly by vapor near ends of furnace tube.
5040.79	.787	6	9	4	1	III A	
5043.75	.761	7	12	5	1	III A	
5044.43	.394	2	1	.....	.....	IV	
5045.58	.582	5	10	4	1	III A	
5053.06	.056	8	*	*	.....	IV?	
5054.29	.261	3	*	.....	.....	IV?	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
5062.27	.285	7	3	1	.....	III	
5064.25	.244	4	Tr.	.....	.....	IV	
5064.79	.836	25	30	20	18	I	Similar to λ 5040.14
5066.15	.174	7	8	3	.....	III	
5068.48	.485	3	Tr.	.....	.....	IV	
5069.50	.592	5	2	.....	.....	IV	
5071.63	.666	7	6	3	.....	III	
5085.50	.513	4	3	1	.....	III	
5087.22	.239	8	8	4	1	III	
5098.56	.492	1	*	.....	.....	IV?	
5103.32	.297	2	*	.....	.....	IV?	
5109.60	.601	4	*	1	.....	III?	
5111.23	.138	1	*	.....	.....	IV?	
5113.60	.617	10	8	5	1	III	
5120.59	.592	12	10	3	.....	III	
5145.61	.636	12	12	6	2	II	
5147.63	.652	10	20	15	15	I A	
5152.35	.361	10	20	15	15	I A	
5173.92	.917	30	30*R*	20	20	I	
5186.49	.497	3	4	1	.....	III	
5188.80	.863	4	.....	.....	.....	V E	
5193.12	.139	35	35*R*	20	20	I	
5194.21	.216	4	6	1	.....	IV A	
5201.29	.260	4	4	1	.....	III	
5206.27	.215	5	3?	2?	?	III?	Blend with *Cr*.
5208.04	.038	3	3	1	.....	III	Probable intensity of *Cr* line subtracted
5210.59	.555	40	40*R*	30	20	I	
5212.47	.503	3	2	1	.....	III	
5218.24	.369	1	Tr.	.....	.....	IV	
5219.86	.875	8	15	12	6	I A	
5222.87	.849	6	4	2	.....	III	
5223.82	.791	6	4	2	.....	III	
5224.50	.471	15	8	6	1	III	
5224.75	.712	6	4	3	.....	III	
5225.12	.101	8	6	4	.....	III	
5226.75	.707	3	.....	.....	.....	V E	
5238.76	.742	6	10	8	1	III A	
5246.28	.310	2	.....	.....	.....	V	
5246.72	.733	3	8	4	.....	III A	
5247.46	.466	5	4	1	.....	III	
5251.10	.085	2	6	2	.....	III A	
5252.23	.276	8	12	10	8	I A	
5255.98	.973	5	4	1	.....	III	
5260.15	.142	3	1	.....	.....	IV	
5263.68	.669	3	3	1	.....	III	
5266.10	.141	10	7	4	Tr.	III	
5282.51	.576	3	5	4	Tr.	III A	
5283.60	.613	8	5	4	Tr.	III	
5284.52	.453	2	4	2	.....	III A	
5295.96	.955	4	5	4	1	III	
5297.40	.407	6	4	3	.....	III	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
5298.58.....	.672	4	2?	1?	.....	III	Slightly affected by *Cr* in furnace
5300.20.....	.152	1	5	2	.....	III A	
5336.94.....	.974	2	.....	.....	.....	V E	
5338.48.....	.517	1	5	3	.....	III A	
5341.67.....	.670	1	*	.....	.....	IV?	
5351.31.....	.261	4	3	1	.....	III	
5366.83.....	.827	2	8	5	Tr.	III A	
5369.85.....	.782	4	2	1	.....	III	
5389.35.....	.371	2	6	5	1	III A	
5390.20.....	.203	3	3	2	.....	III	
5396.80.....	.778	1	8	8	4	I A	
5397.28.....	.344	4	4?	3?	.....	III	Blend with *Fe*.
5404.24.....	.357	2	1	.....	.....	IV	Probable intensity of *Fe* line subtracted
5409.81.....	.823	6	8	5	2	II	
5418.99.....	.979	1	.....	.....	.....	V E	
5419.41.....	.421	1	4?	3	.....	III A	Blend with *C* at high temperature
5426.48.....	.474	3	20	15	8	I A	
5429.35.....	.349	6	6	2	.....	III	
5436.94.....	.938	1	4	3	1	III A	
5438.53.....	.507	1	3	2	.....	III A	
5446.85.....	.797	2	12	10	4	II A	
5449.38.....	.369	1	3	2	.....	III A	
5453.90.....	.860	3	6	4	Tr.	III A	
5460.74.....	.721	4	25	20	15	I A	
5471.41.....	.414	5	6	5	1	III	
5472.92.....	.916	2	7	6	1	III A	
5474.42.....	.436	6	8	6	2	II	
5477.92.....	.901	8	6?	4	1	III	Blend with *C* at high temperature
5481.66.....	.652	6	3	1	.....	III	
5482.10.....	.078	5	9	6	3	I A	
5488.42.....	.374	5	3?	2	.....	III	Blend with *C* at high temperature
5490.37.....	.367	12	10	8	4	II	
5504.10.....	.117	8	3	1	.....	III	
5511.99.....	.872	2	4	2	Tr.	III A	
5512.72.....	.741	25	20	15	8	II	
5514.55.....	.563	20	20	12	7	II	
5514.72.....	.753	25	20	15	8	II	
5565.70.....	.700	9	7	4	1	III	
5644.31.....	.365	18	12	5	.....	III	
5648.80.....	.796	5	6	1	.....	IV	
5662.35.....	.374	12	12	3	.....	III	
5663.11.....	.155	4	4	1	.....	III	
5675.59.....	.647	9	12	3	.....	III A	
5680.15.....	.149	2	3	1	.....	III	
5689.66.....	.694	10	8	3	.....	III	
5702.86.....	.876	6	5	1	.....	III	
5708.41.....	.317	3	3	Tr.	.....	IV	
5712.08.....	.098	4	4	1	.....	IV	
5714.09.....	.120	3	3	Tr.	.....	IV	
5715.30.....	.308	9	6	2	.....	III	
5716.64.....	.671	4	3	1	.....	III	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
5720.64	.666	3	3	1	.....	III	
5739.66	.698	9	5	1	.....	III	
5740.19	.195	4	2	Tr.	.....	IV	
5741.43	.432	1	1	.....	.....	IV	
5753.10	.105	1	1	.....	.....	IV	
5757.10	.037	1	Tr.	.....	.....	IV	
5762.50	.479	4*n*	2*n*	.....	.....	IV	
5766.53	.550	4*n*	2*n*	.....	.....	IV	
5774.23	.250	5*n*	2*n*	.....	.....	IV	
5781.01	.024	2	2	Tr.	.....	III	
5786.19	.193	5*n*	3*n*	Tr.	.....	IV	
5797.70	.715	1	Tr.	.....	.....	IV	
5804.61	.681	5*n*	4*n*	Tr.	.....	IV	
5823.97	.910	3	3	1	.....	III	
5866.69	.675	35	20	30	10	II	
5880.55	.490	5	10	5	1	III A	Relatively weak at high temperature, though slightly wider than at medium temperature
5899.53	.518	25	15	20	6	II	Similar to λ 5867
5903.56	.555	5	10	4	1	III A	
5918.81	.773	10	12	10	3	II	
5922.40	.334	18	15	15	5	II	Similar to λ 5867
5938.05	.035	6	12	6	1	III A	
5942.00	1.985	12	18	12	4	II A	
5953.41	.386	30	15	8	2	II	
5966.06	.055	30	15	8	2	II	
5978.72	.768	25	15	8	2	II	
5988.80	.785	2	3	1	.....	III	
5995.90	.916	2	.....	.....	.....	V	
5996.24	.247	2	2	1	.....	III	
5999.25	.204	4*n*	2*n*	.....	.....	IV	
5999.90	.920	8	5	2	.....	III	May be close double
6064.83	.853	9	15	8	2	II A	
6085.49	.470	20	15	12	4	II	
6091.43	.395	20	9	4	.....	III	
6093.05	.030	4	5	2	.....	III	
6098.92	.870	7	2	Tr.	.....	III	
6121.26	.215	3	4	1	.....	III	
6126.46	.435	20	15	15	5	II	
6138.62	.725	1	1	.....	.....	IV	
6146.44	.445	3	4	2	.....	III	
6149.94	.950	2	2	Tr.	.....	III	
6186.34	.424	3	3	1	.....	III	
6215.48	.360	20	8	2	.....	III	
6220.72	.700	12	7	2	.....	III	
6221.60	.552	8	6	2	.....	III	
6258.34	.322	40	20	20	12	II	
6258.93	.927	50	25	25	15	II	

TABLE I—*Continued*

λ (Exner and Haschek)	Nearest Solar Line (Rowland)	Arc	Furnace			Class	Remarks
			High Temp.	Medium Temp.	Low Temp.		
6261.32	.316	35	20	20	12	II	
6303.93	.985	10	12	6	1	III	
6312.42	.456	10	12	6	1	III	
6318.20	.329	5	9	3	Tr.	III A	
6336.26	.329	8	10	4	1	III	
6366.60	.564	8	10	4	1	III	
6497.95	.840	3	5	3	.....	III A	
6508.37	.380	3	5	2	.....	III A	
6546.52	.479	20	20	8	.....	III	
6554.49	.470	20	20	12	1	III	
6556.31	.308	25	25	15	1	III	
6565.90	.783	4	.....	.....	.....	V	
6575.39	.270	3	.....	.....	.....	V	
6599.35	.353	12	25	15	1	III A	
6743.37	.381	10	30	18	1	III A	
6861.76	.770	6	4	1	.....	III	
7039.060*	.040	6	2	.....	.....	IV	The photographic sensitiveness decreases rapidly in this region. The relative faintness of the medium temperature spectrum and the absence of low-temperature lines may be in part due to this condition
7069.344*	.350	2	1	.....	.....	IV	
7190.208*	.159	2	Tr.?	.....	.....	IV?	
7209.786*	.780	20	20	4	.....	III	
7216.590*	.482	5	5	1	.....	III	
7245.218*	.152	10	10	2	.....	III	
7252.070*	.032	8	8	2	.....	III	
7345.068*	.....	4	4	.....	.....	IV	
7358.028*	.....	3	3	.....	.....	IV	
7364.465*	.....	2	2	.....	.....	IV	

*λ according to Fiebig (International System).

lines for titanium are among the weaker arc lines, being usually below intensity 4, and appear only at the highest furnace temperature, sometimes faintly at medium. Their intensity at high temperature, however, is comparable with that in the arc. *Class V*, which for the iron spectrum embraces a large number of lines, frequently very strong in the arc but faint or absent at the highest furnace temperature, is limited for titanium almost entirely to the enhanced lines. The latter are indicated for brevity as V E. This difference is based on an important feature of the titanium spectrum, in that almost all lines of the arc spectrum, excepting enhanced lines, can be produced with fair strength in the furnace.

GENERAL CHARACTERISTICS OF THE FURNACE SPECTRUM

1. *Lines divided according to initial appearance.*—The titanium lines may readily be classed as low-, medium-, and high-temperature lines, according to the stage at which they first appear, by an inspection of the three columns of Table I devoted to the furnace intensities. On this basis, lines of Classes I and II belong to low temperature, those of Class III to medium, and those of Class IV to high temperature. Lines of Class V for titanium, these being chiefly enhanced lines, are produced with great difficulty if at all by the furnace, requiring the discharge conditions of an electrical source to give them strongly. This basis of division leaves out of account the rate of strengthening with increase of temperature, which is perhaps the most important feature of the classification here used.

2. *Important types of furnace lines.*—Titanium shows comparatively few lines for which a low temperature is especially favorable. Nineteen lines are placed in Class I, ten of which, owing to their relative weakness in the arc, belong to the sub-class I A. When the spectrum was photographed with the 1-meter concave grating, a lens of much shorter focal length was used to focus the light from the tube on the slit than was employed with the large spectrograph. By suitable adjustment of this lens, the slit could be illuminated mainly by light near the end of the furnace tube rather than from the middle of its length. The resulting spectrum was essentially the same as that photographed by the plane grating at the same temperature, but the concave showed an exaggerated intensity for the lines of Class I, as if there were enough difference between the temperatures at the middle and end of the tube to give an unusual strength to these lines. This gave additional evidence of their low-temperature origin.

A large proportion of the strongest lines in the spectrum, both for the arc and for the furnace, belong to Class II. In addition to isolated lines and small groups throughout the spectrum, three notable collections of Class II lines are found near λ 4300, λ 4530, and λ 5000. About the same rate of intensity increase from low to high temperature is observed for most of the lines of this class, and the scale adopted usually places the line given by the high-

temperature furnace as about equal in strength to that of the arc. Multiplying the intensity at medium temperature by 2 and that at low temperature by 3 will give approximately equal values for the arc and the three furnace intensities in the case of most of the Class II lines.

The lines of Class III, which appear distinctly at about 2300° C., are very numerous for titanium. A part of the lines of this class are strong also in the arc, but one of the most striking features of this spectrum is the large number of Class III A lines, especially to the red of λ 4300. The greater part of these are not more than half as strong in the arc as in the high-temperature furnace, while many would not show at all if a strongly exposed arc spectrum had not been used for this comparison. The total number (64) of these Class III A lines is so large as to be accounted for only as showing a real physical condition whereby only a narrow range of temperature excitation is favorable for their production. They do not show at the lowest temperature, and they weaken under the conditions of the arc discharge. The less numerous lines in Classes I A and II A, the former of which is important in the iron spectrum, are similar to those of Class III A in their arc behavior but appear at lower furnace temperatures. If the arc spectrum be considered as resulting mainly from a higher temperature stage than that of the furnace, the light-vibration emitting Class III A lines is given strongly by a degree of this excitation embraced between narrow limits. An alternative view is that there is a fundamental difference in kind between the arc and the furnace in the method of causing the light-vibration. When extensive material for the furnace spectra of a number of elements is available, a comparison with the spectrum of the arc under various conditions may justify a more definite conclusion than it is at present possible to draw.

The nebulous lines, indicated by *n* in the intensity column, are distinctly favored by the arc conditions. Unlike the nebulous lines of iron, the furnace at high temperature gives those of titanium with considerable intensity, but their strength falls off rapidly at medium temperature, where in most cases they are faint. With one exception (λ 3904.99), these lines belong in Classes III and IV. Their diffuseness is usually less marked in the furnace than in the

arc. This probably results from the furnace being operated in a partial vacuum, which should result in a sharper appearance for lines of this kind. An important group in the yellow, however, consisting of λλ 5763, 5767, 5774, 5786, 5804, retains some diffuseness at the high temperature of the furnace.

3. *Change of general intensity with wave-length.*—The data on this point have been obtained from films taken with the 1-meter concave grating, covering at one exposure the visible spectrum. As a salicylic acid filter was generally used, absorbing light of wave-length shorter than λ 3500, there are as yet but few data on the extension into the ultra-violet with changing temperature. From several films taken without absorbing filter, however, the condition appears to be similar to that observed for iron, namely, that lines farther to the violet appear as the temperature rises.

The distribution of line intensities in the visible spectrum also resembles that for iron, and does not correspond with what would be expected if the metallic vapor followed closely the intensity gradation shown by the spectrum of an incandescent solid. With spectra at different temperatures taken on the same film, the red end suffered a greater weakening at low temperature than the violet, lines to the red of λ 5300 being faint at lower temperatures even with the bright spectra of this instrument. It is somewhat difficult to say what should be expected in this regard, on account of the lack of known series and the tendency of lines of certain classes to collect in groups, but it is clear that the strong low-temperature lines do not extend beyond the green, the red end requiring a temperature of about 2400° to show any considerable number of lines.

A comparison of the arc and the furnace in this regard shows a more distinct relation. When an arc spectrum was taken on the same film with that of the furnace, the latter being hot enough to show lines throughout the visible region, the general intensity of the arc spectrum increased toward the violet more rapidly than the furnace spectrum. As the comparison arc could not conveniently be placed in the same position as the furnace tube, a different optical system was required in focusing the image on the slit. Quartz windows and lenses were used throughout for work with the

concave grating, and when the arc was used in front of the furnace and with a lens of shorter focus than that used for the furnace photograph, approximately the same degree of absorption was attained for each source. The steady strengthening of the arc spectrum toward shorter waves in comparison with the furnace spectrum was then very decided. The effect could be varied in an interesting way by placing the arc off to one side and reflecting its light from a silvered mirror through the lens used for the furnace. The decrease toward the violet in the reflecting power of the mirror then served almost to equalize the general intensity of the arc and furnace spectra, though a slight strengthening toward the violet remained for the arc. The comparison of the arc and furnace thus shows a different relation from that which seems to hold for different temperatures of the furnace, the evidence at present being that the movement of higher intensities toward the violet for the arc does not result from temperature difference alone. Evidence from the spectra of other elements is needed on this point.

4. *Absence of the band spectrum.*—The numerous flutings in the titanium spectrum, extending from the green into the red and always shaded toward greater wave-length, are well known. They are given by the metal in the carbon arc when burning in open air, and observers have generally followed Fowler in ascribing them to the oxide, though Kayser[1] considers this as not fully proved, since the oxide, which gives them most strongly, may always be dissociated in the arc or spark, in which case the band spectrum might come from the metal. The furnace, as used in this investigation, does not show the band spectrum, which makes it improbable that this comes from the metal itself. This fact was very clear on many plates and films taken with both the large and small spectrographs, in which strong bands were given by the arc used for comparison, but no trace of these appeared in the furnace spectra, sometimes taken for three different temperatures on the same plate. This shows clearly that vaporization at lower temperature than the arc, at least in the range employed here, does not give the bands for the metal itself. I have not made tests at atmospheric pressure or with any titanium compounds to see under what conditions the

[1] *Handbuch der Spectroscopie*, **6**, 704.

bands will appear in the furnace. The small amount of oxygen remaining when the furnace is pumped out is probably taken up rapidly by the carbon tube, so that the furnace is a favorable source for tests as to whether a pure metal gives a banded spectrum.

COMPARISON WITH THE ARC SPECTRUM

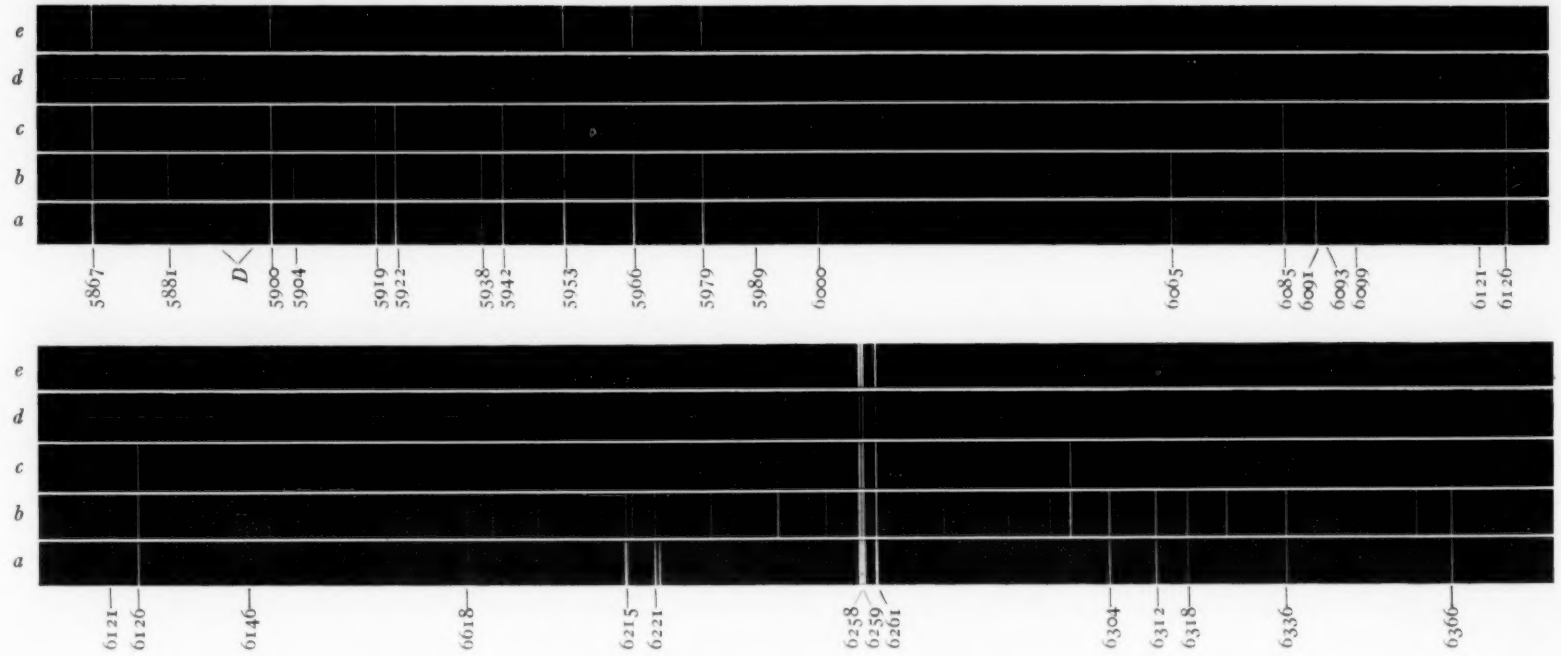
One of the most striking features of the titanium furnace spectrum is its richness in lines as compared with the arc spectrum. The preceding table contains 625 lines. Of these only 9 are placed in Class V. These appear in the arc (all of low intensity), but could not be identified with certainty in the furnace spectrum. Forty-four other lines occur in the arc tables of Exner and Haschek and, strictly speaking, should go into Class V; but they are so very faint, some of them not appearing at all on my arc photographs, that little would be gained by entering them. This means that, aside from the enhanced lines, almost the entire arc spectrum, up to a certain low minimum of intensity, is given by the high-temperature furnace with an intensity so nearly comparable with that of the arc as to justify placing the lines at least in Class IV. The capacity of the furnace to produce difficult lines has not been fully tested. It was shown in a former paper[1] that the stronger enhanced lines between λ 4300 and λ 4600 were given faintly at the highest temperature of the furnace, and longer exposures under these conditions would doubtless add to the list. The furnace, however, is at a decided disadvantage in producing the enhanced lines, which have been shown, especially by the latest experiments with the tube-arc,[2] to require physical conditions distinctly different from those favorable to the arc lines.

In the relative richness of the arc and furnace spectra, titanium offers a strong contrast to the conditions observed for the iron spectrum, where a large number of lines, frequently strong in the core of the iron arc and not to be classed as enhanced lines, required as extreme conditions of furnace temperature as have been needed

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 65; *Astrophysical Journal*, **37**, 119, 1913.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 73; *Astrophysical Journal*, **38**, 315, 1913.

PLATE V



FURNACE AND ARC SPECTRA OF TITANIUM

a. Titanium in carbon arc, exposure 4^{m}.
b. Spectrum of the electric furnace at 2600° C.
c. Spectrum of the electric furnace at 2400° C.
d. Spectrum of the electric furnace at 2150° C.
e. Titanium in carbon arc, exposure 1^{m}.

for the titanium enhanced lines. In the study of the iron spectrum,[1] it was shown that different regions of the arc, from the core to the outer envelope of vapor, affected the relative intensities of various groups of lines in much the same way that they are affected by different temperatures of the furnace. A horizontal section of the arc projected upon the slit of a plane-grating spectrograph thus served to give a classification of lines similar in its main features to that given by the furnace. The titanium arc has also been examined in this way, both photographically and visually. Currents of 5 to 20 amperes were employed with either loaded carbon terminals or electrodes of the metal. The arc under these conditions consists of a brilliant column of vapor of rather uniform luminosity throughout its width. It would be difficult to pick out the furnace classes in the spectrum of this arc, as may be done to some extent with the iron arc. Most of the arc lines show about the same gradual diminution of intensity from the core to the outside of the luminous column, where the lines end rather abruptly, probably as a result of the titanium spectrum requiring a fairly high temperature to show any of its lines. The most decided "core lines" of titanium are the enhanced lines. These are much strengthened by the innermost arc vapor, especially toward the poles. It has been noted that the enhanced lines are given faintly at the highest furnace temperatures. Taken as a whole, a certain measure of agreement is to be observed between the intensities of titanium lines in different parts of the arc and their behavior in the furnace at various temperatures, but the arc is not a favorable source for the division of the lines into classes.

EXPLANATION OF PLATE V

The two sections of spectra in Plate V cover the range from λ 5867 to λ 6366, the spectra being that of the arc (*a* and *e*) and of the furnace at 2600°, 2400°, and 2150° C., respectively. The five spectra were photographed on the same plate and are in many ways typical of the appearance of titanium lines in arc and furnace. The exposure times for the arc were 4^m and 1^m and for the three

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 66, 32; *Astrophysical Journal*, **37**, 270, 1913.

furnace temperatures 3^m, 10^m, and 70^m, respectively. It is thus seen that in this region of the spectrum the absolute brightness of the high-temperature furnace is of the same order as that of the arc. The intensity at medium temperature can be made closely comparable with that at high temperature by trebling the exposure time, while the low temperature brings out these orange and red lines with great difficulty. An exposure of at least 5 hours would have been required to give the low-temperature spectrum the same average strength as the others. The reason for this is not yet clear, but the condition plainly exists for this spectrum and for iron. The fainter arc spectrum (*e*) shows the stronger lines of about the same intensity as the high-temperature furnace, but a number of lines which are distinct in the furnace, such as λλ 5881, 5904, 5919, 5938, 6065, 6304, 6312, 6336, 6366, require prolonged exposure of the arc to give them a strength equal to that in the furnace. The condition holds throughout the spectrum that an arc photograph strong enough to give the majority of the lines of about equal strength in arc and furnace shows only faintly many lines which are strong in the furnace spectrum. The titanium-oxide bands shaded toward the red are visible in the arc spectrum (*a*) but not in that of the furnace. The flutings given by the furnace (*b*) are due to carbon.

SUMMARY

1. The foregoing study of the titanium spectrum covers the range of wave-length from λ 3888 to λ 7364, the spectra given by three furnace temperatures being compared among themselves and with that of the arc with reference to the temperature at which a line appears and its rate of strengthening with increase of temperature.

2. A considerable number of the strongest lines appear at about 2100° C., some of them showing a relatively high intensity at this temperature.

3. A large proportion of the titanium lines appear first at about 2300° C. and usually show a rapid intensification at 2600°.

4. A furnace temperature of 2600° C. brings out almost all lines

appearing in the arc with the exception of the enhanced lines. Traces of the latter can also be obtained under these conditions.

5. The relative weakness in the arc of many furnace lines, observed also for some lines of iron, is an important feature of the titanium spectrum. Most of the lines of this kind are moderately strong in the furnace at medium and high temperatures.

6. Lines of nebulous appearance are high-temperature lines and are usually much stronger in the arc.

7. The strong low-temperature lines occur in the blue end of the spectrum, higher temperatures being required to give distinctly the lines in the yellow and red. The arc spectrum shows a gradual increase toward shorter wave-length in the average intensity of lines as compared with the furnace spectrum.

8. The band spectrum does not appear when titanium metal is vaporized in the vacuum furnace at temperatures ranging from 2000° C. to 2600° C. It is usually ascribed to the oxide.

MOUNT WILSON SOLAR OBSERVATORY
August 30, 1913

THE DEPTH OF THE REVERSING LAYER

By S. A. MITCHELL

In investigating the wave-lengths[1] of the chromosphere from spectra obtained at the total eclipse of 1905, it became necessary to compare the intensities of the lines of the chromosphere with the corresponding lines from Rowland's tables. To make identification of lines more certain, comparisons were made of the intensities of the arc and spark spectra. For each of the 2841 lines measured in the flash spectrum, there are thus given the intensities of chromosphere, Rowland, arc, and spark. In addition to these intensities, measures were made of the heights above the sun's surface of the vapors forming each of the chromospheric lines. Such measures of eclipse spectra give practically the only means available for determining the depth of the reversing layer.

On account of St. John's discussion[2] of "The Distribution of the Elements in the Solar Atmosphere" the depths of the reversing layer and the relative intensities of the spectrum lines assume a rather unusual importance.

St. John's article gave the data for testing Abbot's interesting theory of the formation of the Fraunhofer lines as outlined by him in his book, *The Sun*, pp. 251–252. In brief, Abbot's idea is that the level at which a Fraunhofer line originates is not sharply bounded, but that some portion of the whole depth of the gas is more effective than all the rest in the production of the line.

> From the point of view that no light from the continuous spectrum background appears in the Fraunhofer lines, and that their relative intensities depend upon the light in the lines emitted by the gases, it is evident that light of the wave-length considered, coming from the lowest depths from which it can reach the surface, emerges greatly weakened by absorption and scattering; that light from the lesser depths is greatly weakened because of lower temperature; and that it is the layer between these temperatures that may be considered the effective layer.

The data available to St. John, particularly in regard to the depths of the reversing layer, were, unfortunately, too meager to adequately test Abbot's theory.

[1] *Astrophysical Journal*, 38, 407, 1913.

[2] *Ibid.*, 38, 137, 1913.

38,341

Since the flash spectrum was photographed by a grating without a slit, it was easy to obtain the heights of the vapors forming each line of the spectrum by measuring the lengths of the cusps forming the lines of the flash spectrum. As a matter of fact, this was done[1] by laying a glass protractor on top of a sixfold enlargement of the flash spectrum, and reading off the angular length of the chromospheric cusps. A small table calculated with the sun's semi-diameter equal to 15′50.″7, and the moon's augmented semi-diameter equal to 16′35.″7, gave the corresponding heights in kilometers. It was found that H and K extended 14,000 km above the sun's surface.

Among the results derived from a discussion of the 1905 eclipse spectra (*op. cit.*, p. 494) are the following:

1. The flash spectrum is a reversal of the Fraunhofer spectrum.

2. The flash is not an instantaneous appearance, but the chromospheric lines appear gradually. At the beginning of totality, those of greatest elevation appear first, and at the end of totality remain the last. The "reversing layer" which contains the majority of the low-level lines of the chromosphere is about 600 km in height.

3. Wave-lengths in chromospheric and solar spectra are practically identical.

4. The chromospheric spectrum differs greatly from the solar spectrum in the intensities of the lines.

5. Those differences in intensity find a ready explanation in the heights to which the vapors ascend.

6. Especially prominent in the chromosphere are the enhanced lines which become stronger, mainly because at the heights to which they ascend the vapors are mixed with hydrogen at reduced pressures.

In order to compare the relative behavior of the various elements, a statistical study was made of intensities and heights. Each line of the 2841 lines was taken up in succession, and there were put down in four different tables the intensities arranged according to elements. Each hundred angstroms of wave-lengths were tabulated separately. There were thus given, for each hundred angstroms, the total number of lines for each element, the various

[1] *Ibid.*, **38**, 423, 1913.

intensities of these various lines, from which were readily obtained the total intensities of the lines for each element, and also the average intensities. Four such tables were made, for the flash spectrum, for the lines in Rowland with which these lines were identified, for the arc spectrum according to Exner and Haschek, and also for the spark spectrum from the same authors. With single lines in the flash spectrum identified with single lines in Rowland having single sources, this matter was very simple. The question was to know how to treat blended lines, and lines in Rowland of more than one source. For the case of one line in the flash spectrum corresponding to two lines in Rowland blended together, it was thought that more satisfactory values would be obtained if it was imagined that such a blended line in reality consisted of two lines in the chromospheric spectrum. The intensity of the one actual chromospheric line was divided between the two supposed lines, equally or unequally, as experience dictated. This method gave the total numbers for the various elements slightly different from those obtained in the first discussion.

Instead of giving here the intensities for each hundred angstroms, there are given the results for the whole spectrum from λ 3318 to λ 6191. In the first column is given the element, in the second the total number of lines. In the next four columns are given the average intensities in Rowland's tables, in the chromosphere, and in the arc and spark spectra as given in Exner and Haschek's tables. In the following columns are given various ratios of these four intensities as indicated. Table I does not give a complete list of all the elements found in the flash spectrum. *H*, *He*, and *C* are omitted, and also all elements identified by few lines. On account of similar properties among the elements, which become apparent from the numbers hereby tabulated, the elements are divided into four groups as follows:

Group I contains *Fe*, *Ni*, *Co*, and *Mn*. This may be called the *Fe*-group.

Group II contains *Cr*, *V*, *Ti*, *Zr*, *Sr*, *Ba*, and may be called the *Ti*-group.

Group III contains the rare earths *Sc*, *Y*, *La*, *Ce*, *Nd*, *Sa*, *Er*.

Group IV contains *Ca*, *Mg*, and *Al*.

In taking the average of the intensities of Rowland and the chromosphere it was difficult to know how to treat intensities of o, oo, ooo, etc. The rule was made to treat intensity o as if it were $\frac{1}{2}$, to treat oo as $\frac{1}{4}$, ooo as $\frac{1}{8}$, etc.

TABLE I

INTENSITIES AND RATIOS CORRESPONDING TO THE CHROMOSPHERIC LINES IN THE 1905 ECLIPSE SPECTRUM

Element			Intensities				Ratios of Intensities			
Group	Element	Number of Lines	Rowland	Chromosphere	Arc	Spark	Chromosphere / Rowland	Spark / Arc	Arc / Rowland	Spark / Chromosphere
I	*Fe*	727	3.96	2.14	5.20	1.74	0.54	0.33	1.31	0.82
	Ni	154	2.72	1.09	6.63	2.18	0.40	0.33	2.44	2.00
	Co	101	2.38	1.21	6.54	4.72	0.51	0.72	2.76	3.94
	Mn	89	2.28	2.11	6.63	5.13	0.93	0.77	2.89	2.43
II	*Cr*	198	1.95	1.96	4.48	4.62	1.00	1.03	2.30	2.36
	V	186	1.75	1.72	4.92	5.95	0.92	1.21	2.24	3.46
	Ti	331	2.10	3.36	4.48	4.74	1.60	1.06	2.13	1.41
	Zr	123	1.40	1.80	3.21	5.37	1.29	1.68	2.29	2.98
	Sr	8	2.46	11.2	265.1	126.5	4.56	.....	.....	.....
	Ba	12	3.64	7.07	136.2	161.8	1.94	1.20	37.4	22.8
III	*Sc*	60	2.28	3.73	1.83	13.4	1.64	7.33	0.80	3.60
	Y	52	1.36	2.33	6.93	15.0	1.72	2.17	5.10	6.44
	La	48	1.08	1.72	5.89	10.4	1.60	1.77	5.46	6.05
	Ce	87	1.26	1.61	4.62	3.78	1.28	0.82	3.67	2.36
	Nd	80	1.28	1.67	4.46	4.02	1.31	0.90	3.48	2.42
	Sa	33	0.73	1.17	7.12	3.94	1.61	0.56	9.76	3.37
	Er	24	1.48	1.01	5.78	3.47	0.68	0.60	3.91	3.44
IV	*Ca*	42	44.5	7.82	54.0	46.1	0.18	.....	.....	.....
	Mg	11	13.0	9.20	32.7	115.6	0.72	.....	.....	.....
	Al	3	11.8	5.5	.....	.....	0.47	.....	.....	.....

The reasons for dividing the elements into four groups will be evident by referring to Table I. Group IV, comprising *Ca*, *Mg*, and *Al*, contains elements which have very strong lines in the Fraunhofer spectrum and also in the chromospheric spectrum. This is Group I (*op. cit.*, p. 486), obtained by a discussion of the total numbers of lines in the two spectra.

Reference to the column which gives the ratio of the intensity of the chromosphere to that of Rowland shows that Groups II and III of Table I, comprising *Cr*, *V*, *Ti*, *Zr*, *Sr*, *Ba*, and the rare earths

Sc, *Y*, *La*, *Ce*, *Nd*, *Sa*, and *Er*, are evidently elements whose lines are relatively stronger in the chromospheric spectrum than in the solar spectrum. Together with *H*, *He*, and *C*, these elements form Group II of the previous discussion (*op. cit.*, p. 486).

Fe, *Ni*, *Co*, and *Mn* form a group by themselves where these elements are represented in the solar spectra by stronger lines than are found in the chromosphere.

Before taking up the meaning of this division of the elements into groups, it might be well to speak again of the method of determining intensities in the chromospheric spectrum (*op. cit.*, p. 418). Intensities in Rowland and the chromosphere are both arbitrary. In Rowland the strongest line, K, has an intensity 1000, in the chromospheric spectrum, K has an intensity 100. Necessarily then, the two scales are not the same. Intensities in the chromosphere were actually obtained from negatives sixfold enlarged, as given in Plates XIII to XVIII (*op. cit.*). Such enlargements were at all times compared with a reduced photograph of Rowland's *Atlas* as given in Plate XIV. This comparison insured that on the average the intensities for chromospheric and solar spectra were equal when the intensities were less than 10. Above this, the increased scale of Rowland was manifest. As there are comparatively very few very strong lines, it is felt where so many lines are considered as in Table I that the average will give results free from systematic error. As a matter of fact, 96 per cent of the lines of the chromosphere have an intensity of 8 or less.

Where there are few lines as for *Sr*, *Ba*, *Mg*, and *Al*, or where there are very strong lines as in *Sr*, *Ca*, *Mg*, and *Al*, the averages become unreliable. With these limitations, therefore, it is felt that the numbers in the column giving the ratio of the intensities of the chromospheric spectrum to Rowland have a real signification, and that the division of the elements into groups is a rational one.

Interesting figures are seen in the column giving the ratio of the intensities of the spark to the arc. Intensities for both spark and arc are taken from Exner and Haschek's tables. The great care with which this splendid work of theirs was done, guarantees that on the average, the intensity of the arc for each element would be very approximately equal to the intensity of the spark. That this

is not so for the lines considered in the chromosphere, points to some peculiarity in behavior of the elements and lines considered. Lines which are stronger in the spark than in the arc are called "enhanced" lines. Lockyer's well known list of enhanced lines, though they play an important rôle in the discussion of eclipse spectra (*op. cit.*, p. 487), are in themselves not sufficiently numerous to explain the systematic increases in intensities in Groups II and III in Table I, and they would not at all explain the systematic decrease for the elements of Group I whose lines total over one thousand.

The numbers giving the ratio of the chromospheric intensities to those of Rowland, and the numbers giving the ratio of the intensities of the spark to the arc might be called more or less equal to each other for each element. What is the meaning of the fact that both the columns increase together in Groups II and III over Group I? (On account of the strong lines present in the elements *Ca*, *Mg*, *Al*, and *Sr*, such as H and K, λ 4226, the *b*-group, the *Sr* line λ 4077, etc., the numbers representing these four elements are unreliable, and they are therefore omitted since they do not fairly represent the averages.)

The first meaning that may be drawn from the similarity of the ratios $\frac{\text{Chromosphere}}{\text{Rowland}}$ and $\frac{\text{Spark}}{\text{Arc}}$ is that while the intensities of the Fraunhofer lines as given in Rowland's tables correspond to arc intensities, the intensities of the chromospheric lines correspond more closely with spark intensities than they do with arc intensities. For this reason, there are added to Table I two additional ratios, which give, respectively, the ratios of the intensities of the lines in the arc to those in Rowland, and also the ratios of the intensities of spark and chromosphere. These two last columns might be said to give the intensity of an arc line which would produce a line in the Fraunhofer spectrum of intensity 1, and also the intensity of the line in the spark corresponding to a line in the chromospheric spectrum of intensity 1. For the various elements, these two last columns increase and decrease together.

There are very great differences among the elements. The mean between the two last columns would smooth out the individual differences and render more apparent the behavior of each element.

(This simple mean could be taken at a glance, but since this mean can have no actual signification, it is not inserted in Table I.) *Fe*, then, enjoys the distinction, not only of being represented by the greatest number of lines, but also of having the power to produce lines in the solar spectrum, both Fraunhofer and chromospheric, with greater facility than that possessed by any other element considered in Table I. The difference between *Fe* and the rare earths as a whole is very marked. By reference to Exner and Haschek's tables, it is seen that the rare earths have very many lines in their spectra. It needs a line of approximately intensity 5 in either arc or spark before a corresponding line is found in the Fraunhofer or chromospheric spectrum, while for *Fe*, if there is a line of intensity 1 in the arc, there is found a line in the solar spectrum corresponding to it with an intensity 1 in Rowland, while a line of intensity 1 in the spark spectrum will have a line in the chromospheric spectrum corresponding to it which will likewise be of intensity 1.

That the systematic variations in intensities noted are not merely the results of chance will be more evident if the quantities are arranged according to the atomic weights of the elements.

In Table IV (*op. cit.*, p. 485) was given the periodic table of atomic weights taken from the *Encyclopaedia Britannica*, 11th edition, Vol. **9**, p. 258, under "Element," to which was added to each element the total number of lines of the chromospheric spectrum. Part of the Periodic Table only is given in Table II, where in addition to symbol and atomic weights there are given the total number of lines, and the two ratios of the intensities of chromosphere to Rowland and arc to spark, respectively. Elements in parentheses are not found in the chromosphere.

If we enter the periodic table at *Ca*, we find an element which is represented by the very strongest lines in the sun, in the chromosphere, in the arc, and in the spark. The lines in the sun due to *Ca* are stronger than those of the very light elements *H* and *He*. No satisfactory explanation for this has ever been given. That *Ca* is not dissociated, thus giving rise to a very light element, as has been sometimes thought, is proved by Table II. The elements present in the sun are in such a condition that the atoms differ from the atom of *Ca* by successive gradations. This will be seen by run-

ning in a horizontal row to the right through Table II, and it will be seen that the ratios of chromosphere to Rowland and spark to arc both show a marked tendency to decrease. This same decrease is seen in each of the horizontal rows as one goes to the right. Moreover, from *Ca* in a vertical column downward the two ratios

TABLE II

PERIODIC TABLE OF ATOMIC WEIGHTS

Under each element are given: the atomic weight; the total number of lines in the 1905 chromospheric spectrum; the ratio of the intensity of chromospheric line to Rowland; and ratio of spark to arc.

He 4 15	*(Li)* 7	*(Be)* 9	*(B)* 11	*C* 12						
(Ne) 20	*Na* 23 3	*Mg* 24 10	*Al* 27 3	*Si* 28 7						
(A) 40	*(K)* 39	*Ca* 40 42	*Sc* 44 60 1.64 7.33	*Ti* 48 331 1.60 1.06	*V* 51 186 0.92 1.21	*Cr* 52 198 1.00 1.03	*Mn* 55 89 0.93 0.77	*Fe* 56 727 0.54 0.33	*Ni* 59 154 0.40 0.33	*Co* 59 101 0.51 0.72
(K) 83	*(Rb)* 85	*Sr* 87 8 4.56	*Y* 89 52 1.72 2.17	*Zr* 91 123 1.29 1.68						
(Xe) 131	*(Cs)* 133	*Ba* 137 12 1.94 1.20	*La* 139 48 1.60 1.77	*Ce* 140 87 1.28 0.82	*Pr* 141 1	*Nd* 144 80 1.31 0.90	*Sa* 150 33 1.61 0.56	*Eu* 152 6	*Gd* 157 51 0.89 0.89	
				Dy 162 3	*Nh* ? 1	*Er* 167 24 0.68 0.60				

decrease, also from *Sc* and *Ti* downward. There is thus seen a general decrease in the ratios of the chromosphere to Rowland and of the spark to arc, both to the right and downward, through the periodic table. Above *Ca* in the table is found *Mg*, and on each side of *Mg* are *Na* and *Al*. All three of these elements are represented by very strong lines in all four spectra considered. Above

Ti is found *Si*, and above *Si* is *C*. Though *Si* and *C* are not specially prominent in the sun they are both important elements, *C* from the cyanogen spectrum and carbon bands which appear in sun and chromosphere, and *Si* from the very prominent lines which are found in earlier type stars.

It seems, therefore, that the gradual change from element to element in the periodic table is not one of chance, but one which can find its true explanation only in the constitution of the atom itself. In particular, it seems as if *Ca* was not an exceptional element as has been thought, but is one which occupies its proper place in the periodic table. Likewise it seems as if *V* and *Cr* represent the transition between the group of elements represented by *Ti* and the group represented by *Fe*. The size of the ratios manifested would permit us to put *V* and *Cr* either in Group I with *Fe* or in Group II with *Ti*. For obvious reasons they are put along with *Ti*.

It is with great interest, therefore, that we tabulate the depths of the reversing layers for the various elements, which depths are obtained from the "height of the chromosphere" as given in Table I (*op. cit.*, p. 424). Instead of doing this for each individual element, it was done by groups. Group I contains *Fe*, *Ni*, *Co*, and *Mn*. In Group II are placed not only *Cr*, *V*, *Ti*, *Zr*, *Sr*, and *Ba* of Group II above but also *Ca*, *Mg*, and *Al* of Group IV. (This Group IV is represented by comparatively few lines, and H and K are omitted.) In Group III are the rare earths. In order that the various lines should not be spread among too many classes, the intensities were grouped into four classes as follows: (1) those in which the intensity in Rowland was 2 or less; (2) intensities in Rowland 3 to 5, inclusive; (3) intensities 6 to 10, inclusive; (4) intensities greater than 10. Since the enhanced lines extend to greater heights than those not enhanced, these were treated separately. The results are given in Table III.

In tabulating these heights, it was at once noticed that the heights for all elements were greater at the violet end of the spectrum. Consequently, heights were tabulated separately to the violet side of λ 4900, and to the red side. Though the heights differ, there is shown the same relative behavior throughout the

spectrum, and there are therefore given in Table III the results for the spectrum as a whole.

The table might be explained as follows: 240 of the weakest lines due to the *Fe*-group have an intensity in Rowland of 1.26. In the chromospheric spectrum the average intensity is less and amounts to only 1.07. The average height of these 240 lines is 338 km. Of these 240 lines, only 7 are enhanced. The unenhanced lines extend up to an average of 336 km, while the enhanced lines are relatively much stronger in the chromosphere and extend to greater heights.

Table III shows the following:

1. The average intensity of the lines in the chromosphere is about equal to that from Rowland's tables if the intensity in the latter does not exceed 10.

2. The ratio of the intensities of the chromospheric spectrum to that of Rowland is characteristic for the different groups of elements, this ratio being least for the *Fe*-group and greatest for the rare earths.

3. The difference in heights for the various groups is quite as characteristic. This is best seen by referring to the ordinary or unenhanced lines. The *Fe*-group lines extend to the least heights, the lines of the rare-earth group extend to the greatest heights, in all cases where there are sufficient number of lines to make averages reliable.

4. The enhanced lines are in all cases much stronger in the chromosphere than those not enhanced, and they extend to greater heights. The heights actually depend on the degree of enhancement.

5. The enhanced lines share the same characteristic increase of height from the *Fe*-group to the group of rare earths, as was exhibited by the lines not enhanced.

6. Heights more closely correspond to intensities in the chromospheric spectrum than they do to Rowland's intensities. On the average, a line of intensity 1 in the chromosphere has an approximate height of 350 km, and there is an increase of about 80 km for each unit increase in intensity. Though the determination of heights by measures of the lengths of the chromospheric cusps

TABLE III

AVERAGE HEIGHTS OF THE CHROMOSPHERE ARRANGED ACCORDING TO INTENSITIES AND GROUPS

	SOLAR INTENSITY 2 AND LESS				SOLAR INTENSITY 3 TO 5				SOLAR INTENSITY 6 TO 10				SOLAR INTENSITY GREATER THAN 10			
	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromosphere	Average Height	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromosphere	Average Height	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromosphere	Average Height	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromosphere	Average Height
Fe-group—				km				km				km				km
All lines	240	1.26	1.07	338	243	4.18	1.82	505	116	7.42	3.54	512	23	20.5	6.9	789
Enhanced lines only	7	1.36	3.14	409	7	3.86	9.43	728	2	6.5	11.	650	.....	.....	.....	.....
Unenhanced lines	233	1.26	1.01	336	236	4.19	1.59	395	114	7.43	3.41	510	23	20.5	6.9	789
Ti-group—																
All lines	275	1.07	1.30	385	132	3.79	4.23	588	20	7.45	12.45	1690	8	19.6	27.5	3712
Enhanced lines only	44	1.30	2.78	484	45	4.87	7.94	639	6	8.17	28.0	4350	3	17.3	38.3	6333
Unenhanced lines	231	1.03	1.02	366	87	3.75	2.31	562	14	7.14	5.8	550	5	21.0	21.0	2140
Rare earths—																
All lines	150	0.82	3.10	417	29	3.59	6.15	783	2	6.5	7.0	625	.....	.....	.....	.....
Enhanced lines only	11	1.41	4.28	619	7	3.59	12.29	1464	.....	.....	.....	.....	.....	.....	.....	.....
Unenhanced lines	139	0.77	3.01	401	22	3.59	4.21	566	2	6.5	7.0	625	.....	.....	.....	.....

admits of no great precision, nevertheless it is felt that the large number of lines considered makes the results fairly accurate.

If the sun be considered as a hot body surrounded by cooler vapors extending to various heights but densest nearest the photosphere, then, as was first pointed out by Evershed,[1] the flash spectrum is a progressive exposure. The vapors extending to greatest heights will have relatively longer exposures, and as a consequence flash-spectrum intensities increase with the increase in the heights of the vapors. It would seem, therefore, that the *Ti* lines are stronger in the flash than the *Fe* lines, mainly because the *Ti* vapors extend higher on the average than do the *Fe* vapors. Similarly, it seems that the rare earths, in spite of their higher atomic weights, ascend to still greater heights than do the *Ti* vapors. However, it should not be forgotten that the rare earths are very rich in lines, and in general only the stronger lines are found in either the ordinary solar spectrum or in the flash spectrum.

In his paper on "The Distribution of Velocities in the Solar Vortex," St. John[2] confirms the discovery by Evershed[3] of the displacement of the Fraunhofer lines in the penumbrae of sunspots, and arrives at the following conclusions:

1. The proportionality between displacements and wavelengths shows that the phenomenon is due to the Doppler effect of material of the reversing layer flowing out of spots and of the chromospheric material flowing into the spots.

2. The increase of displacements indicating an outward flow corresponds to a decrease in the intensity of the lines of the reversing layer, and the increase of the displacements indicating an inward flow of the chromospheric gases corresponds to an increase in intensity of the latter lines. A satisfactory explanation seems to be found in a difference in level.

It therefore seems that St. John and the writer both use the differences in heights or differences in level to explain differences in the lines of the solar spectrum.

[1] *Philosophical Transactions*, **197** A, 393, 1901.

[2] *Astrophysical Journal*, **37**, 322, 1913.

[3] *Kodaikanal Observatory Bulletin*, No. 15, 1909.

According to St. John's[1] ideas, however, the rare earths are found in the low-lying regions of the reversing layer. Since they are found comparatively close to the photosphere, they are at a rather high temperature. As a result of this high temperature there is little absorption by the rare-earth vapors, and the Fraunhofer lines are not strong. These high temperatures, however, make more brilliant the lines of the flash spectrum, with the result that the intensities of the rare earths in the flash spectrum are much greater than they are in the Fraunhofer spectrum. Measures of the 1905 eclipse spectrum confirm the increased intensities in the flash spectrum demanded by St. John's theory, *but these measures do not show that the rare earths are found in shallow layers*, but exactly the reverse.

Again, St. John finds that with increasing intensities of the *Fe* lines in the Fraunhofer spectrum there is a decreasing difference of Doppler effect in the spots, which is interpreted as due to a difference of level. This effect seems so uniform that the intensities of the Fraunhofer lines become to St. John a scale whereby he can sound the depth of the reversing layer. In other words, an *Fe* line of intensity 4 in Rowland finds its maximum absorption always at the same level above the photosphere, while lines of intensity 8 have their maximum absorption always in the same level above the photosphere, but this level for lines of intensity 8 is different from the level for lines of intensity 4, and in fact exists above the latter. This idea leads to some important consequences. All lines of *Fe* of intensity 4 in Rowland, and not enhanced lines, must therefore be represented in the flash spectrum by lines of the same height, and this equality in height must entail an equal intensity in the flash spectrum. *Fe* lines of intensity 8 likewise must be represented in the flash spectrum always by lines longer and of greater intensity. Although in general it may be said that the stronger the *Fe* lines are in Rowland, the stronger are those lines when reversed in the flash spectrum and the higher do they extend, yet there are so many exceptions to this, without any apparent cause, that it does not seem possible to make a general rule.

[1] *Astrophysical Journal*, **38**, 174, 1913.

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It would seem, therefore, that the question of heights as given in Table III, and that of relative intensities as given in Tables I and II, must be considered together. It would seem that the process of stellar evolution had advanced to such a stage with the sun that calcium (for some reason) extends higher than any other element, even hydrogen. On account of this great height, H and K are the strongest lines of the solar spectrum. It would further seem that the elements differ from *Ca* and from each other by successive gradations. These differences in the elements seem to find their explanation in the ultimate constitution of the atom itself. In addition to the gradual variation in intensities and heights already shown, we should expect, if the cause is to be found in the atom itself, that the elements close to each other in the atomic-weight table would show also additional common properties. We should expect, for example, that the elements close to *Ca* in Table II would show strong lines comparable with H and K. In fact, they do. Above *Ca* in the table, *Mg* has the *b*-group, *Na* the D lines, *Al* the lines at λ 3944 and λ 3961. Even *Si* has strong lines in stellar spectra at λ 4128 and λ 4131. To the right and below, we have *Sc* with its strong line at λ 4247, *Ti* with its strong lines such as λ 3757, λ 3761, λ 4395, λ 4443, λ 4468, λ 4501, λ 4563, and λ 4572. *Sr* has a strong line at λ 4077 and another at λ 4215. Even *Y* has a strong line at λ 4375 and *Ba* one at λ 4554.

It would seem, therefore, that the elements of the *Ti*-group and those of the rare-earth group both extend to greater heights than do the elements of the *Fe*-group mainly because the atoms of the *Ti*-group of elements and the rare earths are more closely related to the *Ca* atom than are the atoms of *Fe*, *Ni*, *Co*, and *Mn*. If information could be had regarding the changes of pressure, of temperature, and of electrical conditions depending on the differences of elevation, we should advance a long way toward solving some of the curious phenomena connected with the solar spectrum.

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Reviews

Die Atomionen chemischer Elemente und ihre Kanalstrahlen-Spektra. By J. Stark. Berlin: Julius Springer, 1913. Pp. 43; 1 pl.

Many valuable researches have been carried out recently by Stark and his co-workers at Aachen regarding the spectra of the canal rays of various elements. The detailed results are reported in some nineteen articles[1] which have appeared during the present year. As the general conclusions have a significant relation to the problem of the electrical structure of the chemical atom, they are of interest to many who have not the time to read the original papers. For such, Stark has written the pamphlet under consideration, in which he reviews briefly the main experimental results and discusses their significance and bearing on fundamental problems.

From deflection experiments it is known that canal rays are partly neutral atoms and partly positive ions, univalent, bivalent, or multivalent according as they have lost one, two, or more electrons. Stark discovered in 1905 that certain lines of a canal ray spectrum show a Doppler effect, and ventured the hypothesis that such lines are emitted by the positively charged rays. Though this appealed to many as probable, there was really no convincing evidence for it before an improved technique, and especially the discovery by Stark of the advantage of diluting the gas to be investigated with helium made the recent careful study of the shifted lines possible. The valency of the rays emitting a given line cannot be determined from the maximum shift of the line, as was at first assumed; but from a study of the variation of the intensity distribution of the line with the cathode fall of potential, Stark not only is able to show that different series of lines have different carriers but can determine the probable electrical charge of the carriers.

[1] Stark, *V. Deutsch. Phys. Gesell.*, **15**, 809–812, 813–820; *Phys. Zeitschr.*, **14**, 102–109, 454–456, 497–498, 768–770, 779–780, 961–965, 965–969; *Annal. d. Phys.*, **42**, 163–180, 231–237, 238–240; Stark and Kirschbaum, *Phys. Zeitschr.*, **14**, 433–439; *Annal. d. Phys.*, **42**, 255–277; Stark and Wendt, *Phys. Zeitschr.*, **14**, 567; Stark, Wendt, and Kirschbaum, *Phys. Zeitschr.*, **14**, 770–779; *Annal. d. Phys.*, **42**, 278–302; Stark, Fischer, and Kirschbaum, *Annal. d. Phys.*, **40**, 499–541; Stark, Künzer, and Wendt, *Annal. d. Phys.*, **42**, 241–254.

Thus in the case of argon, he found that the red spectrum is emitted by the univalent positive ray, the blue spectrum partly by bivalent and partly by trivalent rays. *Al, B, C, Cl, H, He, Hg, I, K, Mg, N, Na, O, S,* and *Si* canal ray spectra have also been carefully studied. The mercury spectrum is especially interesting as five groups of lines have been distinguished. From their behavior in the canal ray spectrum, Stark concluded that λλ 2537 and 1849 are emitted by neutral atoms and then verified the hypothesis by finding that mercury vapor at low pressures shows a sharp strong absorption line at λ 2537.

Another interesting result to which our author calls attention is that the valency of canal rays is apparently unrelated to their chemical valency. Helium rays may be doubly charged, argon rays trebly charged, and mercury rays quadruply charged. The maximum valency observed under ordinary circumstances seems to depend rather on the atomic weight.

Stark's suggestions as to the arrangement of positive and negative electricity in atoms of various valencies are interesting though, of course, they are meant merely to help make the discussion more concrete and are not to be taken too seriously. He distinguishes two kinds of electrons in every atom, detachable electrons, including the valence electrons, and undetachable electrons. According to Stark's hypothesis, the band spectra are due to the vibrations of the more loosely attached valence electrons, whereas the series lines are emitted by the second group of electrons. Thus he would explain the difference of the Zeeman effect for the two types of spectra and other phenomena he has observed. But though he speaks of two kinds of electrons, he does not mean, of course, to imply any essential difference between them, other than a difference in situation with reference to the atom—a dynamic difference. He concludes with some spectrum evidence to prove the non-elasticity of the collisions of fast canal rays with gas molecules, and with a discussion of the difference between ionization by shock and ionization in electrolytes.

Stark is to be congratulated for having demonstrated the truth of his hypotheses regarding the carriers of series and band spectra, which, when they were advanced some years ago, seemed mere guesses. He not only has been extraordinarily active in accumulating careful experimental evidence, but has been unusually successful in interpreting imperfect data and predicting relations which later research has verified.

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Researches in Magneto Optics. By P. ZEEMAN. New York: Macmillan, 1913. 8vo, pp. 219, figs. 74. $1.60.

This book is one of the Science Monographs which Macmillan & Co. are publishing. In these monographs the authors are supposed to deal mostly with their own researches. Consequently much of this book has appeared as contributed articles in the journals. For the English-reading public, the *Astrophysical Journal* has been the principal publisher.

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Chapter i. Modern Spectroscopes and Resolving Power.
Chapter ii. Magnetic Resolution of Emission Lines. The Direct Effect.
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Chapter v. Phenomena Closely Allied to the Magnetic Resolution of Absorption Lines: (1) Magnetic Rotation of the Plane of Polarization; (2) Magnetic Double Refraction.
Chapter vi. Influence of the Grating and the Slit on the Intensities of the Components; Purity of the Circular Polarization.
Chapter vii. Dissymmetries and Shifts.
Chapter viii. Solar Magneto-Optics.
Chapter ix. The Inverse Effect in Directions Inclined to the Field. Application to Sun-Spot Spectra.
Chapter x. Chemical Elements and Magnetic Resolution. Contributions to the Constitution of the Atom. Bibliography. Index.

The first chapter is very brief and ends with a few remarks upon electromagnets. A student who is unfamiliar with the subject would need a more extended treatment.

In chap. ii the author gives the account of his original discovery. Although the author considers that the work possesses only a retrospective interest, I think it the most entertaining part of the book. For it reveals that clear insight and critical analysis without which he would have arrived at no results whatsoever. Chap. iv is closely related to chap. ii. For so brief a statement of spectral series, the treatment could not be surpassed. Lastly appears a discussion of Runge's Rule upon the periodic distances between components of complex types of separation. The same topic is renewed in chap. x.

Chaps. iii, v, and ix discuss the "Inverse Effect" which follows from Kirchhoff's Law of Emission and Absorption. Upon this particular

topic the author has made extensive observations. From the nature of the case, therefore, the "Inverse Effect" is thoroughly discussed.

In chap. vi we find that a grating may show selective reflection of polarized light in some sections of a given order of the spectrum and not in another. This conclusion has also recently been reached by Ellerman (*Astrophysical Journal*, **38**, 72, 1913). Some years since the reviewer noticed considerable irregularity in the intensity of the ratios of the *p*- and *n*-components of the magnetic separations, while using a glass condensing lens. These irregularities did not appear when a quartz condensing lens was substituted for the glass lens. The reason appeared self-evident. The rays which pass through at different angles and quite different thickness of quartz had suffered very different amounts and kinds of orientation. Most observers, like the reviewer, have used quartz condensing lenses, and a selective polarization of the grating would effect the *p*- and *n*-components in the same way. The experiments of Stock (*Physikalische Zeitschrift*, **10**, 694–697, 1909) remove all doubt upon that point. Dissymmetries and shifts need a larger treatment. The subject needs also a larger investigation with greater resolving power. When this is done, I am prepared to believe that the dissymmetries which I have observed will either disappear or show the spacings to be unequal multiples of small values (intervals).

There is an excellent description and explanation in chap. viii of the broadening of the solar spot lines, observed by W. M. Mitchell; and an equally good brief application of overlapping components, to the magnetic field of sun-spots, discovered by Hale.

This book should be in the possession of everyone interested in magneto-optics. First, the beginning student will find the work clearly outlined, and in it a preparation for the theoretical work of such contributors as Lorentz, Voigt, and Ritz. Secondly, the student who wishes to get a conception of the work in magneto-optics, but has not the time, or perhaps the ability, to take up the theoretical discussions, will find this book to meet his needs, although the non-mathematical student will omit portions of the present volume. Thirdly, the thorough treatment of the "Inverse Effect" will, just now, particularly appeal to students and workers in astrophysics, where a new domain of work has opened up. Fourthly, of course, it will appeal to the physicist. Lastly, there is a complete bibliography, which will be an enormous time-saver to workers in magneto-optics and spectroscopy.

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The Atmosphere. By A. J. BERRY. The Cambridge Manuals of Science and Literature. Cambridge University Press, New York: Putnam, 1913. Pp. 146; figs. 5. 40 cents.

This little book belonging to the long list of Cambridge Manuals of Science and Literature maintains the same standard as the many excellent manuals which have preceded it. Following the style of the other members of the series, the aim has been to present in readable and attractive form some of the salient facts concerning the earth's atmosphere. The development of the science of the atmosphere, from Galileo through phlogistic chemistry to present-day conceptions, has been interestingly traced. As the chief facts of the composition of the atmosphere are a matter of pretty general knowledge, the greatest interest will perhaps be found in the newer and more speculative phases of the subject, especially the character of the upper atmosphere, the primitive atmosphere of the earth, the planetary atmospheres, and atmospheric radioactivity. Here there will be considerable difference of opinion. But such a summary and yet simple outline giving the gist of the subject will be welcomed by many readers.

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